MAGNETISM AND ELECTRICITY FOR BEGINNERS

H. E. HADLEY

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MAGNETISM & ELECTRICITY

FOR BEGINNERS

BY

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PREFACE

THIS little book is primarily intended to meet the requirements of students preparing for the Elementary Stage of the Science and Art Department's Examination in Magnetism and Electricity. The subject has, however, received rather fuller treatment than is required by the syllabus of that subject, so as to include the additional portions needed in examinations for the London Matriculation, Oxford and Cambridge Local, Oxford and Cambridge Joint Board, and College of Preceptors.

The beginner in this subject is often handicapped by a want of knowledge of the elementary facts of Force, Work, and Energy, which are so essential to a clear understanding of electrical principles; an early chapter is therefore devoted to these points.

Electrical Potential generally presents considerable difficulty in the early stages of the study of electricity; an attempt has therefore been made to gradually build up the student's knowledge of this point by introducing it at the outset and on every possible occasion.

The general treatment of the subject is experimental; each step in the argument is brought home to the student

by experiments in which the apparatus is constructed from the simplest material. The student should at every opportunity be encouraged to make the apparatus and repeat the experiments for himself.

The experienced reader will doubtless recognise, in many sections of the book, the author's indebtedness to the teaching of Professors A. W. Rücker, S. P. Thompson, and Sir O. J. Lodge—more especially perhaps in the chapters on Terrestrial Magnetism and on Electrical Machines.

The author gratefully acknowledges the help willingly afforded by Professor R. A. Gregory and Mr. A. T. Simmons, B.Sc., who have brought their kindly and experienced criticism to bear on every portion of the manuscript. He is also indebted to the Controller of H.M. Stationery Office and to the University of London for their permission to insert questions from recent examinations held by the Board of Education and by the University respectively.

H. E. H.

August 1899.

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PART I

MAGNETISM

CHAPTER I

NATURAL AND ARTIFICIAL MAGNETS

Introductory.—A **magnet** is a solid body possessing the property of attracting iron; it has the same power of attracting a few other metals, but to a much less marked extent than in the case of iron.

Magnetism is the science which is concerned with all such phenomena, whether due to a simple magnet or to any other appliance exhibiting similar properties.

Stones possessing the property of attracting iron are found abundantly near Magnesia (in Asia Minor), from the name of which place the word "*magnet*" originated. This stone is now termed **magnetite**; it is an oxide[1] of iron, and contains about 72 per cent of iron; it is distinctly heavy, and is dark-gray to black in colour. Only some specimens of magnetite possess the properties of a magnet, but all are capable of being attracted by a magnet.

Magnetite is also found in considerable quantity in Norway and Sweden, where the remarkable deposits of Dannemora form the source of the pure Swedish iron. The famous Damascus steel was also made from magnetite. In Scotland it is found in a finely granular state, and this also is used for the extraction of iron.

[1] Oxide of iron is a chemical compound formed by the union of the metal iron with the gas oxygen.

In the preliminary experiments which will be described in this chapter it will be found that a piece of magnetite, selected as showing the properties of a magnet, will, when suspended by a thread so as to swing freely, come to rest in a definite position, and point approximately **North** and **South**. This property possessed by magnetite was known to the people of other nations at a very early date; for example, there is every reason to believe that the Chinese were aware of it in the year 2400 B.C. The earliest record of any such knowledge in Europe is found in the writings of a Norwegian who was born in 1068. He describes how Iceland was discovered by a Norwegian Viking, who used ravens as guides, *since in those days seamen in Europe had no lodestone.* The "*lodestone*" (or "*leading-stone*") was the name given to any piece of magnetite which had the properties of a magnet, and this name dates from the twelfth century, when its properties first became known in Europe.

A poem written by a native of Provence in the thirteenth century contains a description of the use of the lodestone as a means of magnetising a needle. The needle, instead of being suspended by means of a thread, is described as being supported on a straw floating in water.

Mariners have an art which cannot deceive
By the virtue of the magnet,
An ugly brownish stone,
To which iron adheres of its own accord.
Then they look for the right point,
And when they have touched a needle on it,
And fixed it on a bit of straw
Lengthwise in the middle, without more,
And the straw keeps it above;
Then the point turns just
Against the star undoubtedly.

. . . .

By this the mariner is enabled
To keep the proper course.
This is an art which cannot deceive.

Dr. Gilbert, of Colchester, really founded the science of magnetism in this country, and published a book on the subject (entitled *De Magnete*) in the year 1600. This book is now esteemed as a work of great historical value.

PRELIMINARY EXPERIMENTS

Apparatus required.—Lodestone, small bar-magnet, several darning needles; fragments of nickel, cobalt, zinc, copper, brass, wood, glass, etc.; iron filings, unspun silk or copper tinsel for suspending the needles.

Magnetic Properties of the Lodestone

EXPT. 1.—Dip the lodestone into a small heap of iron filings; observe how the filings cling to it chiefly at two points (Fig. 1).

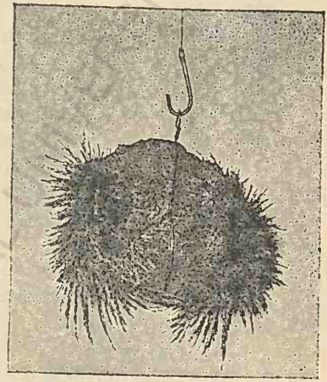


FIG. 1.—A lodestone which has been dipped into iron filings.

Dr. Gilbert named these points the **poles**, and the imaginary line joining these points the **axis**, of the magnet.

EXPT. 2.—Make a suspension for the lodestone, arranged in such a manner that the line joining the two points determined in Expt. 1 may move freely in a horizontal plane.

A convenient form of suspension is made by soldering to each end of a piece of copper tinsel,[1] about 30 cms. long, a short piece of copper wire of medium thickness, which is bent round so as to serve as a hook (Fig. 3); the upper hook hangs from a glass rod fixed in a clamp, the lower hook is attached to a piece of wire which has been wrapped round the lodestone (see Fig. 1). If unspun silk is used instead of copper tinsel, it may be satisfactorily joined to the copper hooks by a fragment

[1] The copper tinsel used for decorating fire-grates is suitable, but it is difficult to obtain a considerable length free from kinks. It may be purchased, specially prepared, from F. Wiggins and Sons, 102 Minories, E.C.

of dry shellac which has been placed on the point of a knife-blade, and heated in a gas flame.

Observe that the lodestone assumes a position in which the axis points in a definite direction, and that when the lodestone is forced to point in any other direction, and afterwards released, it swings to and fro for a short time, and finally comes to rest in its original position (Fig. 2).

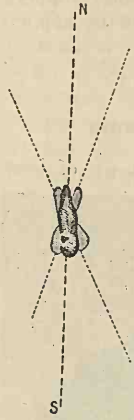


FIG. 2.—A swinging lodestone.

It is important to notice that *this position of rest almost coincides with a line joining the geographical North and South poles.* Mark the end pointing north with a spot of sealing-wax or red paint.

EXPT. 3.—Make a silk-fibre suspension; the fibre may hang from a horizontal glass rod by means of a loop; at the lower end of the fibre is fastened, by means of sealing-wax or shellac, a small piece of paper (2 cms. × 1 cm.) which is doubled back upon itself, thus forming a support sufficient to carry a needle (Fig. 3). Support an ordinary needle horizontally in this suspension; it may swing to and fro, but does not indicate any tendency to come to rest pointing in any one definite direction.

Dip the needle into iron filings; it does not appear to have the power of attracting the filings.

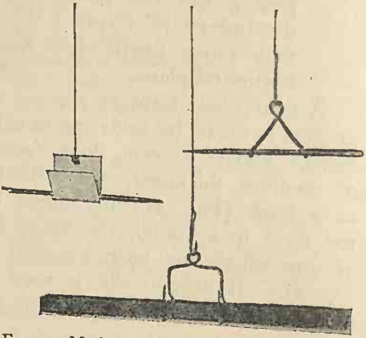


FIG. 3.—Methods of suspending magnets and needles.

These observations indicate that the needle is *not* magnetised, *and the same tests may always be adopted as a means of verifying the presence or absence of magnetisation.*

Note.—In magnetic experiments it is frequently useful to

have a magnetised needle supported on a rigid vertical axis rather than by means of a silk thread. A small pocket compass may be purchased at small cost, but it is too small for class purposes. A very simple arrangement is to fix a magnetised sewing-needle to a short length of thin-walled capillary glass tubing sealed off at one end; the tube rests on the point of a needle passing through a thin slab of cork, which serves as a base; a piece of paper may be attached to the north-seeking end of the needle (Fig. 4).

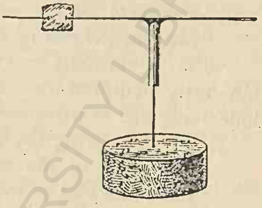


FIG. 4.—A simple form of compass-needle.

EXPT. 4.—Again place the needle in its support, and bring one pole of the lodestone near to one end of the needle; the needle is attracted; if the other end of the needle is tested in same way, the same result is observed (Fig. 5).

This shows that the "magnetic influence" of the lodestone upon iron or steel extends through the space surrounding the lodestone, and does not become evident only when it is placed in actual contact with the iron.

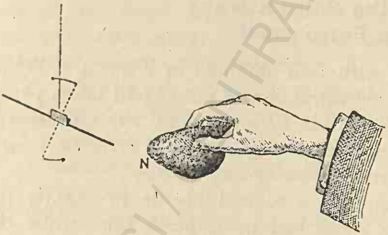


FIG. 5.—Action of a lodestone on an unmagnetised needle.

EXPT. 5.—Resuspend the lodestone, and bring either end of the needle near to the two poles of the lodestone in succession; the needle attracts the lodestone in both cases.

The "magnetic influence" between the lodestone and the needle is quite mutual—it acts equally on both, and that body moves which is free to do so.

EXPT. 6.—Lay the needle on the table, and holding it firmly by pressing a finger on the eye of the needle, rub the

marked pole of the lodestone along the needle from eye to point; lift the lodestone some distance away from the table, and bring it down again on to the eye of the needle, and repeat this operation several times. Replace the needle in its support, and observe how different is its behaviour from that observed in Expt. 3. *It comes to rest with its eye pointing in the same direction as does the marked end of the lodestone.*

So far it certainly resembles the lodestone. It has simultaneously acquired the other characteristic property of the lodestone, viz. *of attracting iron filings* in tufts at its ends.

EXPT. 7.—Bring the marked end of the lodestone near to the point of the needle: *attraction takes place.* Bring the same end of lodestone near to the eye of the needle: *repulsion is observed.* Repeat the observations with the other end of the lodestone; the eye of needle is now attracted, while the point is repelled.

If that end of the lodestone, or of the magnetised needle, which points towards the North is called the **North-seeking Pole**, and the other end the **South-seeking Pole**, the above results may be tabulated in the following words:—

Unlike Poles attract.
Like Poles repel.

Compare this result with that obtained in Expt. 4. When the needle is unmagnetised attraction of either end takes place, but when it is magnetised *one attraction* and *one repulsion* is obtained. *This difference serves to distinguish between a magnetised and an unmagnetised piece of iron or steel.*

EXPT. 8.—(i.) Magnetise a second needle in exactly the same manner as described in Expt. 6, but stroke the needle with the *unmarked* end of the lodestone (instead of the marked end). Suspend the needle, and observe how it comes to rest with its eye pointing in the *opposite* direction to that obtained in Expt. 6 (when the *marked* end of the lodestone was used).

The magnetic polarity generated in that end of the needle which is last touched by the lodestone is of opposite kind to that of the pole which is used for the process.

(ii.) Holding in the hand the needle magnetised in Expt. 6, bring one of its poles near to the ends of the needle magnetised in Expt. 8 (i.), and thereby verify the law of magnetic attraction and repulsion.

It is found, moreover, that any number of needles might be magnetised by one piece of lodestone, without causing the latter to lose any of its characteristic properties. Ages ago it was thought that magnetism was an *invisible fluid*, and that the process of magnetisation involved the transfer of some of this fluid from the lodestone to the piece of iron; but it is now known that the lodestone does not thereby lose any of its magnetism, and consequently no transference of a magnetic fluid can accompany the process.[1]

The terms **Natural Magnet** and **Artificial Magnet** are frequently used to distinguish the lodestone from a piece of iron or steel which has acquired the same properties by artificial means. In the experiments performed, while the lodestone is a "natural magnet," the needles which have been magnetised by mechanical processes are termed "artificial magnets."

Magnetic Substances.—So far only iron or steel have been experimented with, and the observations made have proved that these may be termed *magnetic substances;* but it has not been learnt whether the same phenomena may be observed when other substances are used instead of iron or steel. Are any other metals magnetic substances?

EXPT. 9.—Bring a bar-magnet (or lodestone) in contact with some fragments of *nickel* and of *cobalt;* both are attracted, consequently these also *are* magnetic substances.

EXPT. 10.—Suspend short lengths of *zinc* rod, *wood*, *copper*, *tin*, and of *glass*. Notice none of these are affected by a magnet, and consequently *are not* magnetic substances.

It has been seen that the influence of a magnet can readily pass through air; but air is not magnetic like iron. It has also been found that zinc, wood, copper, tin, and glass are not magnetic; will they also, like air, allow the influence of a magnet to pass through them, and as readily?

[1] Further points regarding the theory of magnetism will be considered in Chap. VII.

EXPT. 11.—Suspend a magnetised needle, and bring the pole of a magnet near to it; hold successively in front of the pole a sheet of copper foil, of zinc foil, of paper, or of wood. In no case is the deflection of the needle affected.

It is evident that magnetic effects are transmitted just as readily through these substances as through air. They may be said to "*conduct*" magnetic effects as completely as air, or their "*conductivity*" is the same. But a very different degree of conductivity is obtained in magnetic substances.

CHIEF POINTS OF CHAPTER I

Magnetite is a chemical compound of the metal iron and the gas oxygen.

Lodestone is the name given to any specimen of magnetite which possesses the characteristic properties of a magnet, viz. (1) of attracting iron or steel filings, and (2) of coming to rest in the magnetic north and south line when free to move in a horizontal plane. The name *lodestone* dates from the twelfth century.

The science of Magnetism was founded by **Dr. Gilbert** in the year 1600.

Artificial Magnets are pieces of steel to which the magnetic properties of the lodestone have been imparted by artificial means. The lodestone is termed a **Natural Magnet** in order to distinguish it from artificial magnets.

The Poles of a magnet are the two points near its ends towards which iron filings are attracted. **The Axis** of a magnet is an imaginary line joining the poles.

The North-seeking Pole is that pole which points towards the *North* when the magnet is freely suspended.

The South-seeking Pole is that pole which points towards the *South* when the magnet is freely suspended.

A steel needle may be made into an artificial magnet by stroking it in one direction with either pole of a lodestone. That end of the needle which is last touched by the lodestone becomes a pole of an opposite kind to that of the lodestone's pole used for stroking.

The same piece of lodestone is capable of magnetising any number of steel needles without losing its natural magnetism.

The Primary Law of magnetic attraction and repulsion is that *Unlike Poles attract* and *Like Poles repel.*

An unmagnetised needle can be distinguished from a magnetised needle by observing that *both* ends are attracted by the pole of a

magnet, whereas one end of a magnetised needle is attracted and the other end is repelled.

Iron, steel, nickel, and cobalt are **magnetic substances.**

Zinc, copper, wood, tin, and glass are examples of **non-magnetic substances.**

The influence of a magnet can be detected at a distance from the magnet, and this influence can be transmitted through non-magnetic substances just as readily as through air.

Questions on Chapter I

1. Describe the appearance of a Natural Magnet, and explain how you would proceed to demonstrate its magnetic properties.

2. (i.) Two steel needles are supplied to you, only one of which is magnetised. How would you determine, by means of a cork floating on water and a lodestone, which of the needles is magnetised?

(ii.) How could you distinguish the needles without the aid of a lodestone?

3. Two sewing-needles are magnetised so that the eye of each is a north-seeking pole. The needles are stuck by their points into separate bits of cork, so that when thrown into water they float upright with the eyes downwards. How will they behave towards each other when floating in this way?

4. You are doubtful whether a steel rod is neutral or is slightly magnetised. How could you find out by trying its action on a compass-needle? If it is found to be magnetised, how would you determine its polarity?

5. A needle is to be magnetised so that its point is north-seeking. Describe carefully how you would do this (i.) with the north-seeking pole, (ii.) with the south-seeking pole, of a lodestone.

6. Two magnetised needles, of equal length, are suspended from their upper ends by threads, so that they hang side by side with their lower ends at the same level. If the lower ends are both north-seeking poles, how will they act upon each other? How will the action be altered when one of the needles is reversed? Give sketches.

CHAPTER II

FORMS OF MAGNETS—METHODS OF MAGNETISATION

Apparatus required.—Bar-magnets. Steel clock-spring. Knitting and sewing-needle. Iron filings. Compass-needle. Suspending stirrup. Soft wax. Glass tubing. A voltaic battery. Long wire-nail. Soft steel wire. Bunsen-burner. Asbestos millboard or iron plate.

In the preliminary experiments the lodestone alone has been used as a means of magnetising small needles; but it is only

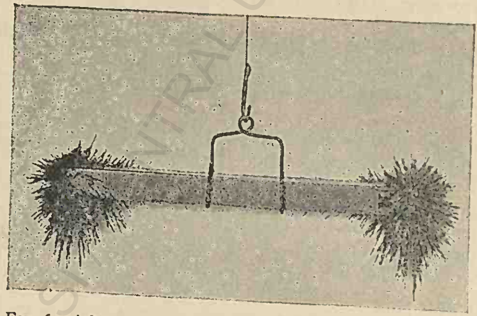


FIG. 6.—A bar-magnet which has been dipped into iron filings.

possible in this way to magnetise comparatively small pieces of steel, and even then the magnetisation is not so marked as would be the case had magnets stronger than the lodestone been used. In future experiments it will be far more satisfactory to dispense with the lodestone, and to use instead some form of artificial magnet, *e.g.* the long bars of magnetised steel

known as **Bar-Magnets** (Fig. 6). These may be obtained either rectangular or cylindrical in cross-section, and, as a rule, the poles are distinguished from one another by the letter N being stamped on the north-seeking end.

Another common form of artificial magnet is the **Horse-shoe Magnet**, in which the steel has been bent into the form of a horse-shoe previous to magnetisation (Fig. 7). The poles of the magnet are at the ends of the horse-shoe, and are thus situated close together.

FIG. 7.—A horse-shoe magnet.

Methods of Magnetisation.—For many purposes it is preferable to use pieces of clock-spring[1] instead of needles for making experimental magnets.

(i.) **Method of Single Touch.**—This is practically the same method as was adopted in Expt. 6.

EXPT. 12.—Break off a piece of clock-spring about 5 or 6 cms. long; hold it firmly on the table by a finger placed at one end (or, better still, fix it to the table by soft wax[2] at the ends), and draw one pole of a magnet along the whole length of the spring, and proceed as in Expt. 6 (Fig. 8). Test the magnetisation (*a*) by means of iron filings, and (*b*) by suspending in a stirrup.

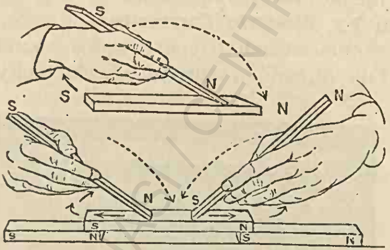


FIG. 8.—Methods of magnetising steel.

[1] Disused clock-springs can readily be obtained from any watchmaker; the steel of a clock-spring possesses that degree of "temper" which is advantageous in the preparation of magnets.

[2] The soft red wax which is used in post-mortem cases is very convenient for the purpose. It can be obtained from most dealers in physical apparatus.

Horse-shoe magnets may be magnetised in this way by drawing the pole of a bar-magnet round the horse-shoe, beginning at one end and completing the stroke at the other end, and repeating this several times. But in practice it is not always found to be satisfactory.

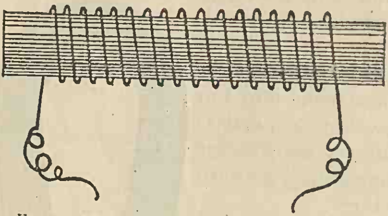


FIG. 9.—Magnetisation of steel by means of an electric current.

(ii.) **Method of Divided Touch.**

EXPT. 13.—Fix a similar piece of clock-spring on the table as in Expt. 12; place the opposite poles of two bar-magnets close together in contact with the middle of the clock-spring, then draw them apart towards opposite ends of the spring. Lift them away, and bring them together again at the centre, and repeat this several times.

A stronger degree of magnetisation is obtained if the spring is supported at its ends on the poles of two other bar-magnets, in each case the poles being of the same polarity as that of the movable magnets above it (Fig. 8).

(iii.) **Magnetisation by Electric Currents.**

If a close spiral of cotton-covered copper wire be wound round a rod of steel (Fig. 9), and a current of electricity sent through the spiral, the steel is far more strongly magnetised than would be the case in either of the previous methods.

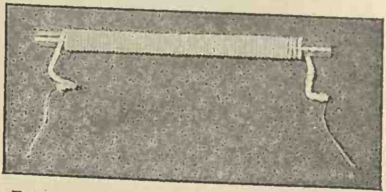


FIG. 10.—A spiral of cotton-covered wire round a glass tube.

EXPT. 14.—Wrap a spiral of cotton-covered copper wire round a piece of thin-walled glass tubing (about 10 cms. long and 0.5 cm. bore) (Fig. 10); place inside the tube a needle or piece

of clock-spring, and pass a strong current through the wire for a few seconds; after stopping the current, remove the needle, and test it for magnetisation.

If the spiral is wound round a solid rod of soft iron instead of the glass tube, then, as long as the current continues, the rod is magnetised to a high degree. Such an arrangement is termed an **Electro-magnet.**

The more common form of electro-magnet is the horse-shoe, which consists of a thick core of soft iron, bent either into the form of a horse-shoe with straight limbs, or into a form resembling three sides of a rectangle. Round each limb is wound a "*bobbin*" of several layers of thick cotton-covered copper wire, the direction in which the wire is wound on the limbs being *opposite* (Fig. 11). While an electric current is passing round the bobbins, a bar of steel may be magnetised by drawing it completely over one of the poles of the horse-shoe. (The polarity of the electro-magnet may be determined by means of a compass-needle.) The result is improved if each end of the steel bar is brought once into contact with the magnet-pole of opposite kind, and withdrawn at right angles to the surface where contact is made.

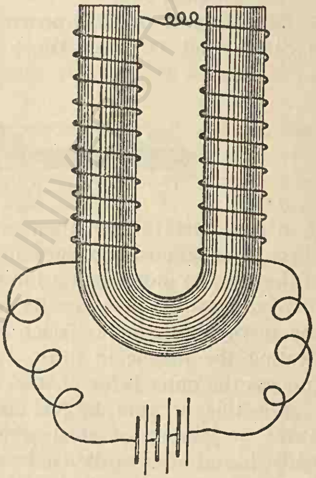


FIG. 11.—An electro-magnet.

A steel horse-shoe is best magnetised by placing it vertically over the limbs of an electro-magnet, with its ends in contact with the electro-magnet poles; while in this position the current is turned on and off three or four times.

Consequent Poles.—Sometimes a magnet may be found which has *similar poles at the two ends;* this may arise through faulty magnetisation, and it may be imitated artificially in a simple way. A magnet showing this peculiarity

will always be found to have the poles of opposite kind somewhere along its length, and these may be located by dipping the magnet completely into iron filings, or by means of a compass-needle placed in a series of positions along its length.

EXPT. 15.—Magnetise a long knitting-needle in four separate parts by the method of Single Touch, and so that a north-seeking pole is found at both ends; another north-seeking pole is also found at the centre, and south-seeking poles at one-quarter of the whole length from each end.

Laminated or Compound Magnets.—In the methods of Single and Divided Touch there is not much advantage

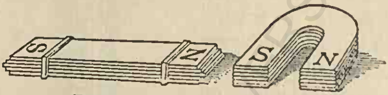


FIG. 12.—Compound magnets.

in using steel thicker than ordinary clock-spring, since the effect of magnetisation does not penetrate into the substance of the steel to more than a limited extent. In fact, the degree of magnetisation of a needle which has been magnetised by the method of Single Touch can be considerably reduced by heating the needle in nitric acid for a few minutes, by which process the outer layer of steel is dissolved.

On this account larger magnets are often made of thin strips or laminæ of steel which have been separately magnetised, and afterwards fixed together. A magnet constructed in this manner is called a *Laminated Magnet* or *Compound Magnet* (Fig. 12).

Magnetic Strength.—The visible effect which a magnet has upon a compass-needle depends not only on the distance between them, but also upon the degree of magnetisation of the magnet. One magnet, A, placed at a certain distance from the needle, may have a greater effect than another magnet, B, when placed at the same distance; in such a case the *strength* of A would be greater than that of B. *The strengths of two magnets may be compared by observing the effect of each upon a compass-needle, the distance between the magnet and the needle being the same in each case.*

Magnetic Saturation.—The degree of magnetisation acquired by a piece of steel depends upon the strength of the magnet which is used in the process; the stronger the magnet the greater the degree of magnetisation acquired. But in every case there is a certain limit, beyond which an increased magnetising power fails to give an increased magnetisation. *Steel or iron is said to be magnetically saturated when it fails to acquire a higher degree of magnetisation, however much the magnetising power is strengthened.*

Destruction of Magnetism.—When a magnet is subjected to rough treatment it loses a considerable portion of its magnetism; for example, if it is dropped on the floor, or struck with a hammer several times, its strength is reduced to a marked extent.

EXPT. 16.—(i.) The effect is far more evident when a piece of fairly soft iron is used rather than steel; for example, a French wire-nail about 7 cms. long is suitable for the purpose. Magnetise the nail by Single Touch, and test its magnetisation by bringing it near to a compass-needle. Strike it several times with a hammer, and test again; it will be found to have lost a considerable portion of its magnetism.

The *twisting*, or *distortion*, of a magnet produces the same effect as hammering.

(ii.) Cut off a length of stout soft steel (p. 16) wire about 14 cms. long, and bend the ends at right angles to the wire, thus: ; this will enable the wire to be readily twisted by hand. Magnetise the straight portion of the wire by the method of Single Touch; test its magnetisation by bringing it near to a compass-needle. Twist the wire to and fro several times, and observe that it has lost all, or nearly all, its magnetism.

If a magnetised needle is heated to bright red heat in a Bunsen (or blow-pipe) flame, and allowed to cool, it will be found to have lost all its magnetism, and will behave like an ordinary unmagnetised piece of steel.

EXPT. 17.—Hold a magnetised needle in a Bunsen flame by means of metal tongs, or by wrapping the ends of a short length of copper wire round the needle; when red

hot remove it, and allow to cool; test its magnetisation by means of a compass-needle.

It will be seen from these experiments that the **degree of magnetisation of a magnet is considerably diminished, or perhaps even destroyed, by rough usage or by great heat.**

Permanent Magnets cannot be made of Soft Iron.—The electro-magnet exemplifies this, for the soft iron cores cease to be magnetised when the current ceases. The student may verify the fact by attempting to magnetise a piece of soft iron (*e.g.* a strip of galvanised iron) by the method of Single Touch. This difference between soft iron and steel will be more fully considered in Chapter III.

Condition of Steel suitable for making Magnets.—Commercial iron and steel may be classified roughly in three groups—(i.) "*cast iron*"; (ii.) "*steel*"; (iii.) "*malleable iron*," "*wrought iron*," or "*soft iron.*" These differ from one another chiefly in the amount of *carbon* contained by them. In cast iron carbon is frequently present to the extent of about 5 per cent; there is less than this in steel, and it is almost completely absent in soft iron. Further differences in character may be given to steel and iron by the processes of "*hardening*" and "*annealing*," which do not appear to be due to any changes in the *amount* of the carbon present, but rather to changes in the *condition* of the carbon. Thus in "*hard steel*" the carbon is apparently *mixed* with the iron, and not *chemically united* with it; but in "*soft steel*" the carbon chemically unites with the iron, and its presence can only be detected by careful chemical analysis. If a piece of steel is heated to bright red heat, and then suddenly cooled by plunging it into water, or, better still, into thick vegetable oil (*e.g.* olive oil), it becomes extremely hard and brittle, and is technically termed "*glass-hard*"; a steel needle in this condition may readily be broken in the fingers. If the red-hot steel is allowed to cool slowly, by covering it with red-hot ashes, and leaving it until the ashes are cool, it becomes somewhat flexible, and may be bent without breaking; it is then known as "*soft steel.*"

In neither of these conditions is steel most suitable for magnetisation, especially if we have no stronger appliance than an ordinary bar-magnet for the process; "glass-hard"

steel is too hard, and "soft steel" is too soft. Intermediate degrees of hardness are obtained by "*tempering*" the steel after it has been glass-hardened; this consists in reheating the glass-hard steel to a temperature below redness, and suddenly cooling it when the requisite temperature is reached. If the surface of the glass-hard steel is carefully cleaned with emery powder, a gradual rise in temperature is accompanied by changes in the "*sheen*" of the surface of the steel. These changes are best seen by holding the steel in such a position that the light from a window or gas-burner is reflected from the surface to the eye of the observer. The tints which successively appear are *light straw* at 220° C., *dark straw*, *brown*, *violet*, and *deep blue* at 320° C.

Long needles are most successfully magnetised if they are tempered to a deep blue tint; short needles are perhaps better when only slightly tempered. It may be added that, for reasons which will be explained in the next chapter, the harder the steel the more difficult is it to magnetise. It is well, therefore, to temper a needle thoroughly if it is to be magnetised by means of another bar magnet, and only to use the steel with less "*temper*" when an electro-magnet is available.

EXPT. 18.—Glass-harden a sewing-needle; clean the surface of the needle thoroughly, and lay the needle on a thin sheet of iron (or asbestos millboard) which is gradually heated by a Bunsen flame; when the desired tint is obtained, suddenly cool the needle again, and proceed to magnetise it.

CHIEF POINTS OF CHAPTER II

A far higher degree of magnetisation can be obtained in artificial magnets than is found in a natural magnet.

The more common forms of artificial magnets are **The Bar-Magnet** and **The Horse-shoe Magnet.**

The simpler **Methods of Magnetisation** are (i.) *The Method of Single Touch*, and (ii.) *The Method of Divided Touch*.

A magnet is said to possess **Consequent Poles** when it exhibits regions of magnetic polarity at other points besides its extreme ends.

A Laminated Magnet is made of thin strips of steel which have been separately magnetised, and afterwards fixed together with like poles in contact.

Magnetisation by means of an Electric Current affords a much more powerful method of magnetisation than either of the simpler methods. The method consists in wrapping a spiral of cotton-covered wire round the piece of steel, and passing an electric current through it.

An Electro-magnet consists of a solid rod of soft iron, round which a spiral of cotton-covered (or silk-covered) copper wire is wound. If a current of electricity is made to pass along the wire, the iron is strongly magnetised. The iron ceases to be magnetised as soon as the current is stopped.

The Magnetic Strength of a magnet is measured by the magnitude of the effect which it has on another magnet placed at a given distance away.

Magnetic Saturation of a piece of iron or steel is obtained when the metal fails to acquire a higher degree of magnetisation, however much the magnetising power is strengthened.

The degree of magnetisation of a magnet is considerably reduced, and perhaps even destroyed, by *rough usage* or by *great heat.*

If a piece of steel is heated to red heat, and suddenly cooled, it becomes *glass-hard*, but if cooled slowly it becomes *soft*. Neither of these conditions is the most suitable for making magnets. An intermediate degree of hardness is obtained by slowly reheating glass-hard steel up to a moderate temperature; this process is known as the **tempering of steel.**

Questions on Chapter II

1. Why is an artificial magnet usually preferred to a natural magnet in order to magnetise a steel needle?

2. A needle is to be magnetised so that its eye acquires north-seeking polarity. State fully how you would proceed to do this (i.) by the method of Single Touch, (ii.) by the method of Divided Touch.

3. How would you experimentally determine whether a magnet has consequent poles or not?

4. What conclusion would you come to if a magnetised piece of steel, when suspended, does not tend to come to rest pointing in a north and south direction? If the steel is now broken into two parts, would you expect them to behave, when suspended separately, in the same manner as the unbroken piece of steel? (Give diagrams to explain your answer.)

5. Why is it possible to obtain a stronger magnet if it is laminated than if the same amount of steel is made into a solid magnet?

6. Describe briefly the appliances you would use in order to magnetise a piece of clock-spring as strongly as possible.

7. What is meant by the term *magnetic saturation?*

CHAPTER III

MAGNETIC INDUCTION

Apparatus required.—Bar-magnets and horse-shoe magnet. Compass-needle. Iron filings. Several strips of galvanised iron (10 cms. × 1 cm.). Small wire nails. Sewing-needles and knitting-needle. Suspending stirrup. Steel pen-nibs. Pieces of steel and soft iron of exactly the same dimensions. Iron nail. Blow-pipe (or Bunsen-burner).

Magnetic Induction.—The simple experiment (Expt. 4) in which a suspended unmagnetised needle is influenced by the pole of the lodestone held near to it, may afford still further information. When the pole is brought near either end, the attraction which is observed might, at first sight, suggest that it was simply a case of "Unlike Poles attracting," and that we should find "repulsion" when the other end of the needle is tested. But on completing the experiment in this manner we again find "attraction." It would seem either that an entirely new phenomenon is being brought into play, or that "*latent*" magnetism in the needle appears *when the magnet is brought near one end*, and again appears, *but in a reversed direction*, when the other end is tested. To decide this point, it will be necessary to test the polarity of the *distant* end of the needle while the magnet still remains in its first position. To enable the effects to be more marked, use a much larger needle, *e.g.* a darning-needle, 12 or 14 cms. long.[1]

[1] A very suitable material for induction experiments is the thin "*galvanised iron*" which is used in making biscuit-tins and tobacco-tins; this material is made by dipping sheets of thin soft iron into a bath of

EXPT. 19.—Hold the darning-needle or strip of galvanised iron in line with the magnet's axis, the end not quite touching the north-seeking pole; bring the distant end of iron in contact with iron filings; some filings cling to the end (Fig. 13). Reverse the strip of iron, and again test.

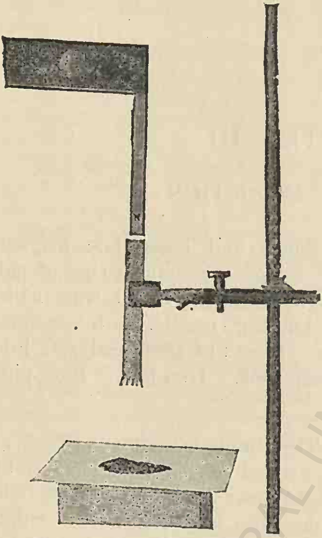


FIG. 13.—To illustrate Expt. 19.

EXPT. 20.—With the magnet and strip of iron still in the same relative position, bring the distant end of the strip near to the poles of a compass-needle; there is attraction of the south-seeking pole, and repulsion of the north-seeking pole.

The iron consequently obeys both the confirmatory tests for magnetisation, and the magnetisation may be either "*temporary*" or "*permanent.*"

EXPT. 21.—Remove the bar-magnet, and repeat the tests for magnetisation; we find that the strip now behaves like an unmagnetised piece of iron.

It is evident that the strip of iron actually *becomes a magnet when it is near to the bar-magnet*, but ceases to be one as soon as the magnet is removed. We say that magnetism has been *temporarily induced* in it, and that its behaviour in Expts. 19 and 20 is due to "*magnetic induction*" from the bar-magnet.

When a piece of iron or steel is magnetised by induction, the end farthest away from the inducing pole acquires polarity of the same kind, the nearer

molten tin. Strips about 10 cms. long by 1 cm. wide are convenient. All the experiments are more evident if the strips are brought into actual contact with the magnet.

end acquires polarity of the opposite kind, to that of the nearest pole of the permanent magnet.

If the piece of iron is really a magnet, then *it* also should be capable of inducing magnetism in a second piece of iron held near to it.

EXPT. 22.—Support horizontally on blocks of wood a bar-magnet and two pieces of soft iron in line with the magnet's axis; test the polarity of the induced magnetism in the more distant piece of iron (Fig. 14).

We can now understand the cause of all the phenomena of attraction which a magnet displays towards magnetic sub-

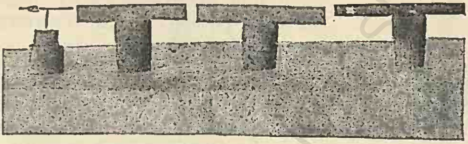


FIG. 14.—To illustrate Expt. 22.

stances. The experiments prove that **magnetic induction always precedes attraction**, and that these phenomena are all in accordance with the simple law that "*Unlike Poles attract.*"

Magnetic Induction depends upon the relative positions of the bar-magnet and soft iron. Mere proximity to a magnet is not the only condition requisite for induced magnetisation, for much depends upon *the part of the magnet towards which the soft iron points.*

EXPT. 23.—Bring a strip of soft iron towards the centre of a magnet, and pointing at right angles to its axis. No induced magnetisation can be detected. If the bar is held at same distance from the magnet, but pointing towards one of the poles, the induced magnetisation is quite evident; and it is possible to observe that the iron acquires most magnetisation when its length is in line with the magnet's axis.

Therefore, induced magnetisation in a piece of soft iron due to a bar-magnet depends both upon the *distance* apart, and also upon the *relative directions* of the magnet and the soft iron. (See also Expts. 25 and 26.)

The phenomenon of magnetic induction can be illustrated by several most instructive experiments, which can be carried out with the simplest appliances; it may be useful to suggest one or two at this point.

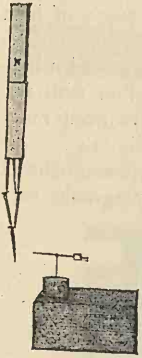


FIG. 15.—To illustrate Expt. 24.

EXPT. 24.—Clamp a large bar-magnet in a vertical position, note the polarity of the lower end, and hang from it a strip of galvanised iron. Bring into contact with the iron a number of small wire-nails, and notice how long a chain of nails can be supported. The iron and each nail are temporarily magnetised. Test the polarity of the extreme end of the chain by means of a compass-needle (Fig. 15).

EXPT. 25.—Bring near to the end N the south-seeking pole of a second bar-magnet. This second magnet will also act inductively on the iron and nails, but the induced polarity will be opposite to that already present. The magnetisation of the iron and nails is consequently weakened, and most of the nails fall off (Fig. 16).

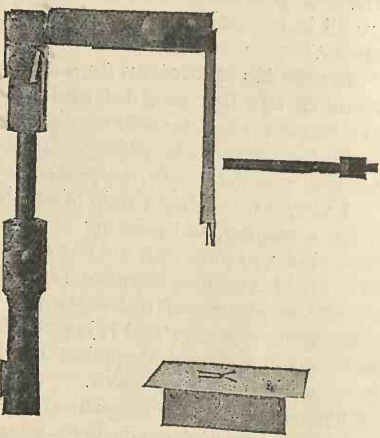


FIG. 16.—To illustrate Expt. 25.

EXPT. 26.—Replace everything as in Expt. 24. Now place the south-seeking pole of a second bar-magnet just below the end of the chain of nails. We can now add two or three more nails; the induction due to the south-seeking pole tends to strengthen that originally present,

and consequently the induced magnetism is increased (Fig. 17). Remove the south-seeking pole, several nails will fall off; if the north-seeking pole of the second magnet be now placed close to the end of the chain, more nails will fall off (Fig. 18).

EXPT. 27.—Suspend from the pole of a vertically-clamped magnet a bunch of sewing-needles, or three or four strips of galvanised iron. Notice that the lower ends of all the needles have similar polarity, and mutually repel

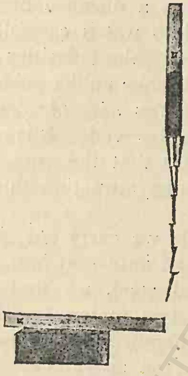


FIG. 17.—Expt. 26.

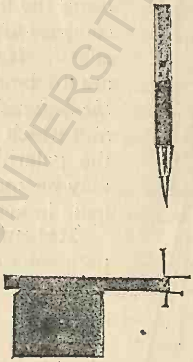


FIG. 18.—Expt. 26.

each other—the needles consequently bunch outwards (Fig. 19).

In Expt. 25 it is evident that induced magnetism can be produced in a piece of iron which is already in a state of induced magnetisation. Can we cause magnetic induction in a piece of iron which is a *permanent* magnet?

EXPT. 28.—Feebly magnetise a long knitting-needle, and suspend it in a stirrup. Hold the pole of a strong bar-magnet some distance away, and observe the repulsion between similar poles. Rapidly bring the magnet to within an inch of the repelled end of the needle, when *the original repulsion is converted into a strong attraction.*

Evidently *magnetic induction can produce a reversal of the polarity of a magnet.*

At a great distance the induced magnetisation is weak, and its effect is hidden by that of the permanent magnetisation; but when the magnet is brought near to the needle the induced magnetisation is not only sufficient to neutralise the permanent magnetisation, but completely overpowers it.

This phenomenon, unless it is guarded against, often gives rise to incorrect conclusions in an experiment. It is most important in all such experiments to *gradually* bring the magnet from a distance near to the compass-needle, and to watch carefully for the effect. If the two ends, the polarities of which are to be compared, have unlike polarity, then *the induced magnetisation aids the true attraction* which should be observed. It is only when the polarities are *like* that the true repulsion may be masked by the attraction due to magnetic induction.

FIG. 19.—To explain Expt. 27.

Retentivity.—If we carry out simple experiments on magnetic induction both with soft iron and with hard steel, we find that the behaviour of these two materials differs considerably. This difference is not so easy to observe as long as the substance remains in actual contact with the magnet, but becomes very evident when it is removed from the neighbourhood of the magnet. The soft iron, when removed, immediately ceases to show magnetic properties. We may say that *soft iron soon forgets the treatment to which it has been subjected.* But hard steel, after removal, continues to exhibit magnetic properties—iron filings will still cling to its ends. In fact it continues to exhibit all the properties of a magnet. We may say that *hard steel does not forget its previous treatment.* To remove the induced magnetisation from steel we must subject it to rough treatment, *e.g.* strike it several times with a hammer, or drop it on the floor, or in some other way disturb the arrangement of its minute particles.

The power of retaining magnetisation after the

magnetising force is withdrawn is termed **Retentivity.** Some specimens of steel will retain as much as 90 per cent of the original magnetisation; so also will soft iron, *if not subjected to the slightest mechanical disturbance.*

EXPT. 29.—Clamp a bar-magnet vertically, and suspend from the pole a piece of soft iron, from the lower end of which several wire nails are hanging. Carefully remove the soft iron, and observe the nails soon drop off, showing that the magnetisation induced in the soft iron is rapidly lost.

Now attach a *short* piece of hard steel to the pole of the magnet, and hang from the steel as many nails as possible. Carefully remove the steel, and notice that nearly all, or perhaps all, the nails continue to hang from the steel. The magnetisation in the steel remains, even though withdrawn from the influence of the bar-magnet.

If a piece of hard steel of suitable size is not to hand, the effect may very well be shown with ordinary steel pen-nibs.

Susceptibility.—It was stated above that the difference in behaviour of soft iron and steel *when still under magnetic induction* was not so easy to observe, but it can be made more evident by modifying the experiment slightly. When a piece of soft iron is brought near to the pole of a compass-needle, the permanent magnetism in the latter *induces magnetism* in the soft iron, and the compass-needle is attracted—the stronger the induced magnetism the greater is the deflection of the needle. Substitute a piece of hard steel of the same size for the iron, and observe that the deflection of the needle is *less*, because the induced magnetism in the steel is less.

EXPT. 30.—Suspend a magnetised needle just above the level of the table, and place a bar of *unmagnetised* steel horizontally with its end near to the north-seeking pole of the needle, and its length perpendicular to the needle's axis.

Now place the soft iron (of similar size to the steel) on the opposite side of the needle, and alter its distance from the pole until the needle again points to the north (Fig. 20). The soft iron completely neutralises the

effect of the steel, although it is much farther away from the needle than the steel is.

We say that the **susceptibility of soft iron is greater than that of steel.** The susceptibility of a magnetic sub-

FIG. 20.—Expt. 30

stance is *the relative degree to which it will become magnetised when placed near to a permanent magnet.*

Effect of Heat on Magnetic Induction.—We have already learnt that excessive heat will destroy the power of a permanent magnet to retain its magnetism. *Will heat*, in the same way, *prevent the acquirement of induced magnetism?*

EXPT. 31.—Heat an iron nail to bright redness in a blow-pipe flame, and while still hot, touch the nail with the pole of a bar-magnet, and repeat the contact several times while the nail is cooling. The nail is not attracted in the least until it has considerably cooled, when it suddenly reacquires the property of being attracted by the magnet.

Hence, *when iron is heated to a high temperature, it no longer possesses the power of being magnetised by induction.*

Effect of Vibration on Induced Magnetism.—In the previous chapter it was found that rough usage, or any cause of violent vibration, diminished the permanent magnetism in a bar-magnet. Does rough usage prevent the acquirement of induced magnetisation?

EXPT. 32.—Place a strip of soft iron in line with the axis of a magnet, but not quite in contact with it. Verify the presence of the induced magnetism, and also its disappearance as soon as the iron is gently removed from the neighbourhood of the magnet. Again place it near to the magnet, and while in this position strike it several times with a hammer. When removed to a distance it will be found that the induced magnetism is still present—in fact, the iron has acquired slight

permanent magnetisation. Since the *retentivity* of soft iron is small, a few taps with a hammer will suffice to remove every trace of this permanent magnetism.

Hence, when near to a magnet, vibration or any disturbance of the particles in a bar of soft iron will aid the acquirement of induced magnetisation, and may even give rise to slight permanent magnetisation, which is readily destroyed when the iron is afterwards subjected to vibration at a distance from the magnet.

FIG. 21.—Horse-shoe magnet and keeper.

Keepers or Armatures.—The use of the *keeper* or *armature* is a practical application of the phenomenon of Magnetic Induction. If a horse-shoe magnet is allowed to remain for a considerable time with its poles unprotected, its degree of magnetisation slowly diminishes; but if a short length of soft iron is placed so as to connect the poles, and in contact with the entire length of the pole-faces, this liability to loss of magnetisation is prevented. Any piece of soft iron serving this purpose is called a **keeper**. So long as it is in contact with the poles of the magnet the soft iron is also a magnet by induction. The stronger the induced magnetisation in the keeper the better is its purpose fulfilled.

In Fig. 21, N induces south-seeking polarity at the near end of the keeper, and north-seeking polarity at the distant end. The pole S has the same effect, consequently N and S *help each other*, and produce a much greater degree of induced magnetisation than if they were acting alone.

The two poles of a bar-magnet cannot be connected in this simple manner, but the difficulty is overcome by keeping the bar-magnets in pairs, and placing them parallel to one another with opposite poles together. A piece of soft iron is placed at each end of the pair (Fig. 22).

Manufacturers of magnets always supply keepers with the magnets.

(The theoretical explanation of the utility of the keeper will be given in a later chapter.)

Lifting Power of a Magnet.—The force which must be applied to separate a keeper from its magnet depends not only upon the strength of the magnet-pole, but also upon the degree of induced magnetisation in the keeper. From the above statements it is readily seen that a horse-shoe magnet will support, by means of its keeper, a much heavier weight than will a single bar-magnet of the same dimensions; experiments go to show that it will support three or four times as heavy a load.

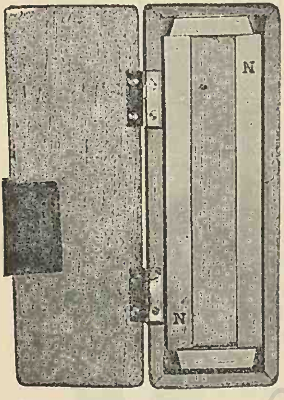


FIG. 22.—A pair of bar-magnets and keepers.

The lifting power also depends to some extent upon *the accuracy of contact* between the magnet-poles and the keeper, and upon *the shape of the surfaces* of contact. A keeper will support a greater weight if its surface of contact is shaped like an inverted letter V instead of being quite flat. (For the true explanation of this phenomenon reference must be made to a more advanced text-book.)

Precautions in using Keepers.—(1) Never omit to replace the keeper when an experiment is finished.

(2) Carefully wipe the magnet-poles before attaching the keeper, so as to remove any iron filings or solid matter from the surface. It is important that the contact between the keeper and pole-surfaces should be as perfect as possible.

(3) Occasionally rub the surfaces of the magnets and keepers with oil to prevent rust.

(4) Never allow the keeper to *slam* on to the magnet-poles; it is very liable to weaken the magnet.

(5) Vigorous removal of a keeper is *not* injurious; in fact it is more beneficial than otherwise.

Chief Points of Chapter III

Magnetic Induction.—A piece of iron or steel is *temporarily* magnetised when held *near* to a bar-magnet, but the magnetisation disappears as soon as the magnet is removed. The end of the iron or steel which is nearest to the inducing pole acquires polarity of the opposite kind, and the distant end acquires polarity of the same kind.

Induced magnetism in one piece of iron or steel can induce magnetism in other pieces of iron or steel.

Magnetic Induction always precedes attraction.

Magnetic Induction depends upon the relative positions of the permanent magnet and the pieces of iron or steel.

Magnetic Induction due to one permanent magnet may be neutralised, partially or completely, by that due to another neighbouring magnet.

A Reversal of the polarity of a magnet may be brought about by Magnetic Induction.

Retentivity (or **Coercive Force**) is the power which iron or steel has of retaining its magnetisation.

The Susceptibility of a magnetic substance is the relative degree to which it will become magnetised when placed near to a permanent magnet.

Great Heat prevents magnetic induction.

Vibration, or any rough treatment, aids the acquirement of induced magnetism.

Magnetic Keepers assist permanent magnets to retain their magnetisation.

The Lifting Power of a magnet depends not only upon the strength of the magnet, but also upon the degree of induced magnetisation in the keeper.

Questions on Chapter III

1. A bar-magnet is held vertically, and two equal straight pieces of soft iron wire hang downwards from its lower end. The lower end of each of these wires can by itself hold up a small scrap of iron; but if the lower ends of both wires touch the same scrap of iron at the same time, they do not hold it up. What is the reason of this? (1881.)

2. Two similar rods of soft iron have each of them a long thread fastened to one end, by which they hang vertically side by side. On bringing near to the iron rods, from below, one pole of a strong bar-magnet, the rods separate from each other. Explain this.

3. If a compass-needle is deflected when a steel bar is brought near it, how can you find out whether the deflection is due to magnetism already possessed by the bar, or to the bar becoming magnetised by the compass-needle at the time of the experiment? (1886.)

4. You have given to you two rods, one of soft iron, the other of hard steel; also a compass-needle and a bar-magnet. Describe experiments with the things provided whereby you could find out which was the iron and which was the steel rod.

If the rods are of the same size, describe how you could dispense with the bar-magnet and still distinguish the iron from the steel.

5. A bar-magnet is laid on a table with its **N** end projecting over the edge. A soft iron ball clings to the under side of the projecting end. State and explain what happens when the **S** pole of a second magnet is brought (i.) above and near to the **N** pole of the first, (ii.) below and near to the iron ball. What will happen if the **N** pole of the second magnet is brought below and near to the iron ball?

6. A compass-needle and a straight strip of soft iron of the same length as the compass-needle are fastened together so as to be in contact with each other at both ends. Will the force which tends to make the combination point north and south be the same as that which would act on the compass-needle alone? Give reasons for your answer. (1887.)

7. A piece of soft iron, placed in contact with both poles of a horse-shoe magnet at the same time, is held on with more than twice the force with which it would be held if it were in contact with only one pole of the same magnet. Why is this? (1886.)

8. A bar-magnet is laid upon the table, and a soft iron bar of about the same length as the magnet is hung horizontally just above it by a flexible string. What will be the effect on the soft iron bar if a second bar-magnet be laid on the table and gradually brought near the first at right angles to it, and with its north-seeking pole pointing to the middle of the first magnet? (1885.)

9. Two bars of soft iron are so placed to the east and west of the north pole of a compass-needle that the needle still points north and south. If the iron to the east of the needle is replaced by a bar of hard steel of exactly the same size and shape as itself, will the direction in which the needle points be altered? If so, in which direction will it move? and why? (1888.)

10. One pole of a magnet made of soft iron and only feebly magnetised is found to be repelled by the north pole of a strong magnet when the latter is some distance away, but to be attracted when the magnets are brought close together. Explain this. (1901.)

CHAPTER IV

FORCE, MASS, WEIGHT, WORK, AND ENERGY

Apparatus required.—Set of gram weights (100—.001). Metre scale and yard-measure. V-shaped block of wood to serve as fulcrum for metre scale to exemplify Law of Moments. Model for experimental proof of Law of Moments. Protractor. String. Pulley-wheel.

Force is an expression adopted, unfortunately, as a mode of expression in both mental and mechanical phenomena. This wideness of application renders it necessary to explain with accuracy the extent and meaning of the word as used in this little book, and to indicate not only its strict scientific sense, but also how this interpretation forms the keystone to physical measurement.

FIG. 23.—A stone supported by a string.

Let us examine a simple case of mechanical force. A stone supported by a string, which is held in the hand, *tends* to fall towards the earth—the earth exerts a *force of attraction* on the stone, and this force is termed the *force of gravitation.* Why does the stone remain at rest? Muscular exertion is required to prevent the fall of the stone; the hand must exert as much force in holding the stone up as the earth exerts in trying to pull it down. If the muscular exertion of the hand ceases, the stone falls downwards, in accordance with the force of gravitation. When the stone was at rest, the two forces were acting in opposite directions. If the mass of the stone is doubled, then, to still remain at rest, the muscular

force of the arm must also be doubled. The stone is only at rest because the forces are equal and opposite (Fig. 23).

Since a force may be completely defined by stating its point of application, its direction, and its magnitude, it may be represented diagrammatically by means of a straight line. All these conditions are fulfilled in a diagram by drawing a straight line from a certain point, in a certain direction, and of a certain length. Thus, the two cases of a stone supported by a string, mentioned above, may be fully represented by Fig. 24.

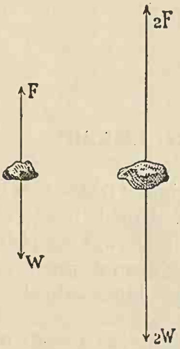


FIG. 24.—Examples of equal and opposite forces.

When both F and W are acting, a **Force may be defined as that which tends to produce a movement of any body.** If the string is cut, then W only is acting, and the stone commences to move in the direction in which W is acting; the tendency of the force W at once becomes evident.

When fragments of iron are lifted by a magnet, they only remain supported so long as the force of magnetic attraction is stronger than the attractive force of the earth upon the fragments. If the attractive force exerted by the magnet suddenly becomes weaker, the fragments will fall off in obedience to the greater force of gravitation.

Bearing this in mind, it does not follow that because a body is at rest that no forces are acting on it; for example, if the pole of a magnet be placed a short distance above a heap of small iron nails, though no visible effect on the nails is obtained, the force of magnetic attraction is still acting, and it is only hidden by the fact that there is also the greater force of gravitation keeping the nails at rest.

Mass and Weight.—In the year 1686 the **Law of Gravitation** was enunciated by Newton in the following terms:—"*Every particle in the universe attracts every other particle with a force acting in the direction of the line joining the two particles; the magnitude of this force is proportional to the product of the masses of the two particles, and inversely proportional to the square of the distance between the particles.*"

By saying that *the force varies inversely as the square of the distance* is meant that if the distance of the particles apart is *doubled*, the force of attraction will be reduced to *one-fourth* of its original value; if the distance apart is *trebled*, the force is reduced to *one-ninth*, and so on.

This *law of inverse squares*, as it is often termed, is applicable to other physical phenomena besides that of Gravitation; it is certainly true of magnetic phenomena, and an experiment will be described in the next chapter (p. 55) which will prove that the magnetic effects between two neighbouring poles vary inversely as the square of the distance between them.

The earth itself is a huge mass always exerting an attraction on neighbouring masses. *The force of attraction which the earth exerts on any mass is called the* **weight** *of the mass.* If the distance of the small mass from the earth is increased the *weight* will be less; this effect has been verified by suspending a mass from a spring-balance and observing that the spring is extended more when the mass is at the foot of a mountain than when the mass is at the top of a mountain. In these two cases *the mass is the same*, but the *weight varies;* the difference in the weight would, however, be very small, and it is sufficient for ordinary purposes to regard the weight as being constant in all parts of this country.

Mass may be defined as *the quantity of matter* in a body.

Units of Length, Weight, and Force.—When we express the weight of a substance, we say that it weighs *so many* more times than the weight of a pound mass. The weight of a pound is our *unit of weight* in England. Also the yard is our *unit of length*.

In nearly every other country the unit of mass is the *gram*, and the unit of weight that of the gram. The unit of length is the *centimetre*. These units are also universally used in scientific work. The centimetre is the $\frac{1}{100}$th part of the *metre*, which is equivalent to 39.37 inches; so that the centimetre is equal to 0.3937 inch, or 1 inch is approximately equal to 2.54 centimetres. The *gram* is defined as the mass of a cubic centimetre of water at a certain temperature, and is equivalent to about 15.43 grains.

It is also necessary to have a *unit of force*, so that any other force may be described as being equal to so many units of

force. In practical work it may be sufficient, at first, to take the *weight of* 1 *gram* as the unit of force;[1] then, if a force is described as being equal to twenty units of force, it will be clearly understood that the force is equal to the weight of 20 grams.

Parallelogram of Forces.—If a body tends to move in two different directions simultaneously, it does not follow either, but moves in an intermediate direction. If the two directions of the original movements are represented by straight lines, the length of each being proportional to the rate with which the body tends to move along that line, and if the parallelogram of which these two lines are adjacent sides is completed, then the body will move to the opposite corner of the parallelogram; its path will be represented by the line joining the two opposite corners: this line is called the diagonal.

For example, imagine a man standing at the point A (Fig. 25) in a railway truck which moves uniformly in one

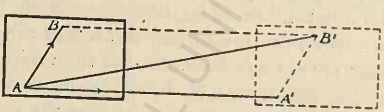


FIG. 25.—The parallelogram of velocities or of forces.

second from A to A′, and imagine that at the same moment the man begins to walk from A to B. At the end of the time he is neither at A nor at B; his position is B′, and the path he has actually traversed is AB′. The position B′ might have been arrived at if the man had stood still at A, while the truck carried him to A′, then if the truck stopped and the man commenced walking in the direction originally intended he would again arrive at B′. The only difference in these two methods of arriving at B′ is that in the first case the movements of truck and man take place simultaneously, but in the second case they take place consecutively.

Since motion of a body is produced only by the application of a force, and the degree of motion is proportional to the

[1] In physical measurements it is more usual to use the *absolute unit of force* (called the Dyne). The *dyne* is equal to about the weight of 1 milligram.

magnitude of the force acting, the same principle of the parallelogram may be used to determine the combined effects of two forces which act upon a body simultaneously. Hence, **if two forces act on a body, the result is the same as if one single force, represented by the diagonal of the parallelogram constructed from the two forces, acted upon the body.** This diagonal force is called the **Resultant.** The original forces are called the **Components.**

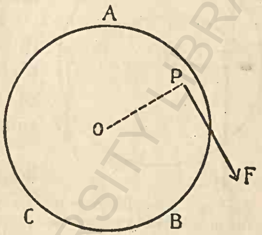


FIG. 26.—The moment of F round O is F×OP.

The Moment of a Force.—When a body, free to move, is acted upon by a force, it will move in obedience to that force in the direction in which the force is acting. This result ceases to hold good when the body is *fixed at one point.* For example, suppose the disc ABC (Fig. 26) to be fixed at the point O, round which it is able to rotate, and that a force F is acting at the point P, in a direction perpendicular to OP. The force will cause the disc *to rotate* round O. The arm OP represents the *leverage*, or *purchase*, which the force has round O; the longer OP is the greater is the leverage of the force. The power to produce rotation depends upon the magnitude of both the force and the arm, and is expressed numerically by the product of the force and the length of the arm. This product is called the **Moment of the Force round O**; or

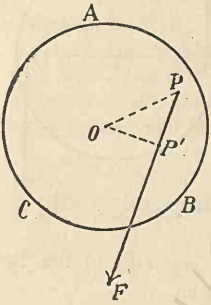


FIG. 27.—The moment of F round O is F×OP′.

Moment of Force = Force × Arm.

If the force does not act in a direction perpendicular to OP, the moment round O is no longer equal to *the force* × OP; its perpendicular arm is now OP′ (Fig. 27), and its moment is equal to *the force* × OP′. It is evident from the diagram that

the point of application of the force may be moved from P to P′ without in any way altering its effect. Hence *the arm* of the force may be defined as *the perpendicular distance of the fixed point from the line of action of the force.*

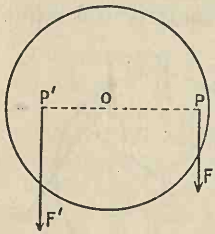


FIG. 28.—The difference of the moments of two forces.

If the force, or its line of action, pass through the fixed point, then it has no leverage round the point. The length of the arm is *zero*, and therefore the moment of the force = *zero*.

The Sum of the Moments of two Forces.—(i.) *When the forces are acting in the same direction* (Fig. 28), and on opposite sides of the fixed point. In this case the forces tend to produce rotation in opposite directions, and the direction of rotation will depend upon *the difference of the moments* of the two forces. If the moments are equal the disc will remain at rest, and this equality of moments may be written

$$F \times OP = F' \times OP'.$$

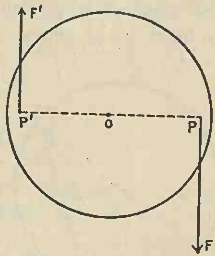


FIG. 29.—A couple.

(ii.) *When the forces are acting in opposite directions* (Fig. 29), and on opposite sides of the fixed point. The two forces tend to produce rotation in the same direction. The rotational effect will depend upon the *sum of the moments* of the two forces, and the total moment may be written

$$(F \times OP) + (F' \times OP').$$

If F and F′ are equal to one another, they constitute what is termed a **Couple.** *A Couple may be defined as two equal and parallel forces acting in opposite directions.* The total force-moment may be written $F(OP + OP')$, or $(F \times PP')$. Hence, *the moment of a Couple is equal to one of the forces multiplied by the perpendicular distance between the two forces.*

The principle of the Couple is most important in the study

of magnetism, and frequently affords a correct explanation of the results observed in experimental work.

Its effect on a comparatively heavy body can be readily understood from Fig. 30. Imagine the couple F_1F_1 acting on the disc. The disc will move with increasing velocity into the position indicated by F_2F_2; the velocity acquired will carry it beyond the position F_2F_2, and the couple, now acting in the opposite direction, will gradually bring it to rest in the position indicated by F_3F_3. The disc will now move in a similar manner back into its original position, and this cycle of movements will be repeated while the disc is slowly brought to rest by the friction in the axle at O; its final position of rest is indicated by F_2F_2.

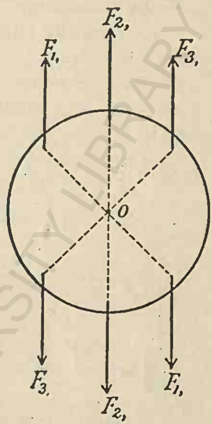


FIG. 30.—The action of a couple on a freely-suspended body.

It is also evident that the rapidity with which the disc will vibrate to and fro depends upon the strength of the forces F_1F_1. The stronger the forces are the more rapidly will the disc vibrate.

Experimental Proof of the Law of Moments

EXPT. 33.—Obtain a thick cardboard disc ABC (Fig. 31), 40 cms. diameter; behind the centre of the disc fix a cork, D, through the axis of which a tightly-fitting knitting-needle has been passed. The projecting end of the needle serves as an axis for the thin wooden lever NS; through the centre of the lever tightly fix a short piece of glass tubing, of slightly larger bore than the knitting-needle, which enables the lever to move with less friction than if the lever itself is allowed to touch the needle. At the point N fix a short length of stiff wire through the lever to enable threads to be readily attached. One quarter of the disc is covered with a piece of *squared*

paper, so that the lengths of the *arms* OP and OP′ may be measured.

Rigidly support the disc by fixing the free end of the

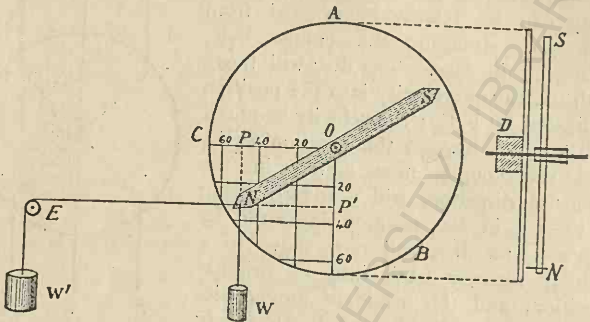


FIG. 31.—Diagram of apparatus for proving the law of moments.

needle in a clamp. Clamp a second piece of knitting-

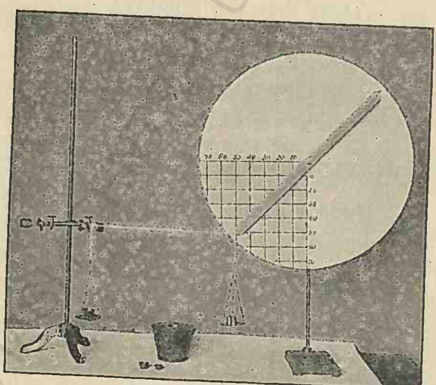


FIG. 32.—Apparatus for proving the law of moments.

needle at E, and let it carry a short piece of glass tubing over which is passed the thread supporting the mass W′. During the experiment vary the clamp at E in height,

so that the thread connecting N and E is always horizontal. The complete apparatus is represented in Fig. 32.

Hang 20 grams at W, and 10 grams at W′; measure the lengths OP and OP′. Keep W the same, and make W′ equal to 20 grams; again read OP and OP′. Repeat these measurements with varying values of W′, and tabulate the results in the following manner[1]:—

W	W′	OP	OP′	W×OP	W′×OP′
23	13	37.5	63	816.5	819
23	23	52	51	1196	1173
23	33	59	40.5	1357	1336.5
23	43	64	33.5	1472	1440.5

Within the range of experimental error, it is evident that (W × OP) is always equal to (W′ × OP′). The

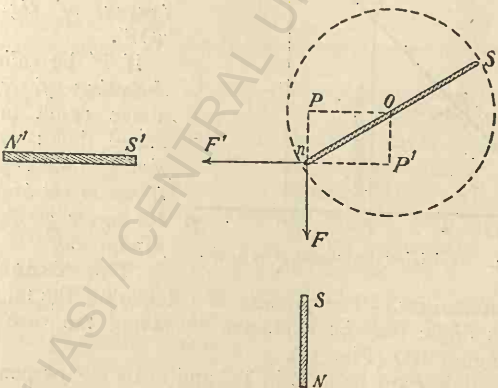


FIG. 33.—The law of moments applied to a magnetic experiment.

lever is in each case at rest, and the *moments of the two forces* W and W′ are always equal and opposite.

[1] In this experiment the weights of the scale-pans should be previously determined and added to W and W′.

Application of this Principle to a Magnetic Experiment.—If a compass-needle is acted upon by two external magnets, as in the diagram, it comes to rest in a position such that the moments of the two forces F and F′ are equal and opposite (Fig. 33).

The moment of F $= F \times OP = F \times nP'$.

" " $F' = F' \times OP'$.

Hence $(F \times nP') = (F' \times OP')$;

or $F' = F \times \dfrac{nP'}{OP'}$.

In an actual experiment it is difficult to measure nP' and OP' separately, but the angle nOP' can be readily measured if a graduated circle is fixed under the needle. *The ratio* $\dfrac{nP'}{OP'}$ *is called the tangent of the angle* nOP'.

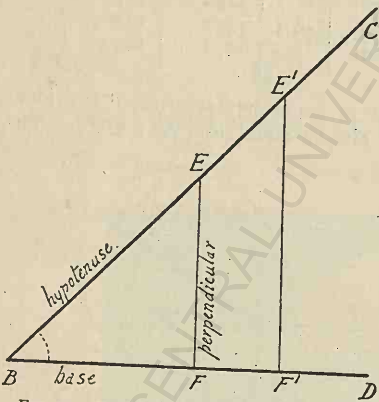


FIG. 34.—Explaining the tangent of an angle.

If F′ be called the *deflecting force*, the above result may be stated thus :—*The deflecting force is proportional to the tangent of the angle of deflection produced.*

The Tangent of an Angle.—The process of calculating the tangent of an angle may be explained by taking the case of the angle CBD (Fig. 34).

Select any point E in BC and draw EF perpendicular to BD. EF, BF, and BE are termed the *perpendicular*, the *base*, and the *hypotenuse* respectively, of the right-angled triangle EBF.

The ratio $\dfrac{\text{length of perpendicular}}{\text{length of base}}$ is *the tangent of*

the angle CBD, or

$$\text{tangent of CBD} = \frac{EF}{BF}.$$

It might be thought that the value of the tangent would be different if the point E had been placed somewhere else along the line BC. Had E been placed at E′, then E′F′ is longer than EF, but BF′ is at the same time proportionately longer than BF, so that $\frac{EF}{BF}$ has exactly the same value as $\frac{E'F'}{BF'}$. Hence the numerical value of the tangent of an angle is quite independent of the size of the arms of the angle.

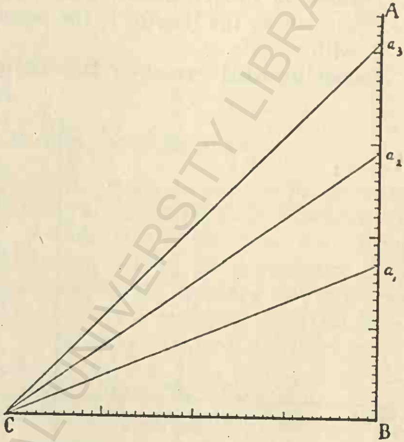


FIG. 35.—Graphical method of calculating the tangent-value of an angle.

EXPT. 34. *Examples of Tangents.*—Draw AB perpendicular to BC (Fig. 35), and divide each into millimetres by means of a scale. With a protractor describe several angles, a_1CB, a_2CB, a_3CB, etc. etc.

For each angle measure the lengths of the perpendicular, and calculate the value of the tangent. Tabulate the results thus:—

Angle.	Perpendicular.	Base.	$\frac{\text{Perpendicular.}}{\text{Base.}}$

The numerical value of the tangents of all angles have been accurately calculated, and can always be found in books of *Mathematical Tables*. In experimental work, a far more accurate figure is obtained by referring to the table of tangent-values than by using a protractor and measuring the lengths of the perpendicular and the base with a scale.

Experimental Proof of the Tangent Law.—This law has already been stated in the following terms:—*The deflecting force is proportional to the tangent of the angle of deflection produced.* It may be experimentally verified in the following manner:—

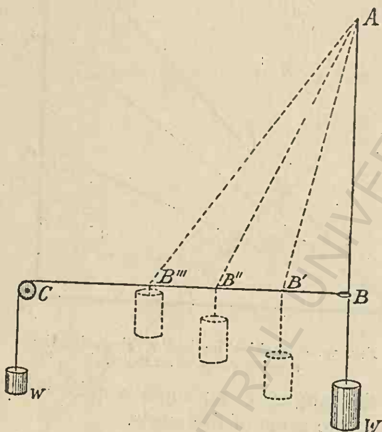


FIG. 36.—Diagram of an experimental proof of the tangent law.

EXPT. 35.—Fix a nail at a point A near to the top of a blackboard, and suspend from it a string which carries a mass W. The string passes through a smooth ring B, which is connected to one end of a second string, and this passes horizontally over a pulley-wheel fixed at C; to the free end of this string a mass w is attached.

W remains unaltered during the experiment, and may conveniently be equal to 100 grams. The mass w is varied, and may be made equal to 20, 30, 40, and 50 grams. Before taking any measurements the ring at B is moved until the string BC is horizontal. The results may be tabulated in the following manner:—

w	$\frac{w}{W}$	BB′	$\frac{BB'}{AB}$

Work, Power, and Energy

Work.—When a man endeavours to raise a heavy mass from the floor, he applies a force, acting vertically upwards, by means of the muscles. At first the mass does not move, because the force of gravitation pulling the mass downwards is greater than the force exerted by the muscles upwards; so far no work has been done by the muscles. If the force applied is exactly equal to the force of gravitation, the mass no longer exerts any pressure on the floor, but it does not move. It is only necessary to increase the upward pull to the slightest degree in order to make the mass commence to move upwards; then the muscles begin to do work.

When the mass has been raised one centimetre, a certain amount of work has been done; when it has been raised through two centimetres twice as much work will have been done.

The work done is proportional to the force overcome and to the distance through which the force has been overcome; or,

Work = Force overcome × Distance.

Unit work is done when unit force is overcome through unit distance.[1]

The pole of a magnet exerts a *force of attraction* on the opposite pole of a second magnet. If these two poles are forcibly drawn apart, *work* has to be expended in doing this, and may be measured by the force overcome multiplied by the distance. So also, if the two poles are allowed to approach,

[1] The *absolute* unit of work is called the **Erg**, and is equal to the work done by one dyne in moving through one centimetre.

the force of attraction is able to do work in drawing the two magnets together.

Power.—A unit of work may be done rapidly or slowly—it may take a fraction of a second or it may take several hours. In these two cases the *rate at which work is done* is very different. **The rate at which work is done is called the Power.**

Unit Power is capable of doing one unit of work in one second.

Energy.—When a mass is falling freely through the air, work is being done on it by the force of gravitation. What becomes of the work done? Is it absolutely disappearing and being lost, or is it assuming some other form? The latter is the correct assumption, for the work done on the body is simply being stored up. Owing to its motion, the mass acquires *a capacity for doing work*, which may be utilised by making the falling mass turn machinery. It is for this reason possible to make falling water turn a water-wheel. *This capacity for doing work is called* **Energy**; and if the energy is due to the *actual motion* of the mass, it is called **Kinetic Energy.**

Potential Energy.—Work has to be expended in lifting a heavy mass from the floor to the table. When the mass is on the table it is at rest; it has no velocity, and therefore *no Kinetic Energy*. What has become of the work done in lifting the mass? It is not lost, but is simply stored up, and the work so accumulated will reappear if the mass is allowed to fall to the floor; it is, in fact, capable of doing the work which has been expended upon it, if allowed to do so. Its *latent energy is due to its position* on the table above the floor; we say that the mass has **Potential Energy**, or energy *due to position*. If the mass is allowed to fall freely to the floor this Potential Energy reappears as Kinetic Energy, which is directly capable of doing work.

When two magnet-poles of similar kind are placed close together, there is, as has been seen, a force of repulsion tending to separate them; either pole has Potential Energy due to its nearness to the other pole; and if one of the poles is free to move, its Potential Energy will become Kinetic Energy in the retreating magnet, which will be capable of doing work owing to its motion.

The two cases of the heavy mass on the table and of the magnet-pole may be made more distinct from each other by saying that the heavy mass has *gravitational* Potential Energy, and that the magnet-pole has *magnetic* Potential Energy.

Other Forms of Energy.—Energy may exist in many different forms; thus mechanical energy, heat, magnetism, electrification, electric currents, and chemical action are all forms of energy. All these different forms are mutually convertible; thus we can transform work into heat or into electrification, and *vice versa*.

Examples. *Work and Electrification.*—(i.) If a stick of sealing-wax is rubbed on the coat sleeve the wax becomes electrified and heated. The work done in rubbing the sealing-wax partly reappears as electrification on the sealing-wax, and this is capable of doing work, for it is able to pick up fragments of paper from the table.

(ii.) The work done by a water-wheel may be used to drive a dynamo, and so to generate an electric current.

(iii.) The electric current from a dynamo may be used to drive an electric motor, which enables the electric current to be converted into work.

Thus Electrification (also the Electric Current) and Work are mutually convertible.

The Electric Current and Heat.—(i.) When coal is burnt in a steam-boiler, the chemical action of the burning coal generates heat, which is converted into mechanical energy in the steam-engine, and this becomes a current of electricity when the engine is made to drive a dynamo.

(ii.) If a current of electricity is passed through a thin wire, the wire becomes hot, and may be made sufficiently hot to give out bright light. This is so in the *incandescent lamp* used in electric lighting.

Conservation of Energy.—No form of energy can be generated without an equivalent loss in the same, or some other, form of energy; also, if energy disappear in one form it will reappear in some other form. This fact is an absolute law which may be expressed in the following terms:—**The total amount of Energy in the universe is a constant**

quantity which can never be increased or diminished, although its form may be changed.

Examples.—(i.) Mechanical work is done when two magnet-poles of opposite kind are dragged apart; they may be kept apart for any length of time, but the mutual attraction between them is still able to reproduce the work done in separating them, so soon as they are allowed to move freely and approach one another. So long as they remain apart the energy is potential, and due to the relative position apart of the magnets.

(ii.) A magnet is able to do work in lifting small fragments of iron, but it only acquires the capacity for doing this when mechanical work has been expended in magnetising it.

(iii.) Electric currents may be generated by mechanical work, by heat, or by chemical action in what is termed a *Voltaic Battery*. When the student has acquired knowledge of these phenomena, it will be clear that a current of electricity cannot be generated without the expenditure of an equivalent amount of energy in the form of mechanical work, of heat, or of chemical action; and *vice versa*, that the passage of a current of electricity, or the disappearance of electrification, is always accompanied by the appearance of its equivalent in the form of heat, chemical action, or of mechanical work.

Surfaces of Equal Potential.—When a heavy mass is resting on a horizontal table, the force of gravitation and the equal and opposite reaction of the table are the only forces acting on it. If the table is smooth no work is required to be done in order to move the mass into different positions on the surface of the table, since no work is thereby done against, or by, the force of gravitation. It may generally be stated that *no work is done on a body when it is moved in any direction at right angles to the force (or resultant force) which may be acting on it.*

In all positions on the table the mass will have the same *potential energy;* hence the top of the table may be termed a **Surface of Equal Potential.** This holds good however large the table may be; the only necessary condition is that all

points of the surface must be at the same height from the ground.

If a second table is supported on the first, and the heavy mass is lifted up on to the top of the second table, the work done on the mass will increase the potential energy which it already possessed when resting on the lower table. Thus, if A and B (Fig. 37) are the two tables, and the vertical distance between them is h cms., the work done in lifting the mass W through the height h will equal Wh gram-cms., and this quantity is the amount of increase of potential energy when the mass is lifted from A to B.

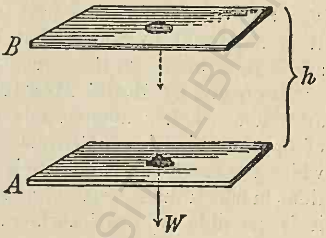


FIG. 37.—The gravitational potential on table B is greater than that on table A.

The surface of the upper table is also a surface of *equal potential*, but the *magnitude* of the potential is greater than

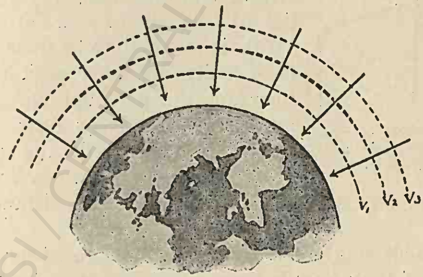


FIG. 38.—The earth surrounded by surfaces of equal gravitational potential.

that on the lower surface. A vertical series of these surfaces may be considered in exactly the same manner, each surface being one of equal potential, but the actual value of the potential on each surface being greater than that on the surface immediately below it.

Instead of being limited in area, each surface may be

imagined to be invisibly extended in all directions, while each remains at a constant height above the earth's surface. The earth would then be surrounded by a series of concentric spheres, as shown in Fig. 38 by the dotted lines V_1, V_2, and V_3; the surface of each sphere is a surface of equal potential. It is important to notice that at any point these surfaces are at right angles to the direction of the force at that point.

Surfaces of Equal Magnetic Potential.—The force of attraction which a magnet-pole exerts on a neighbouring pole of opposite kind is exactly analogous to the force of attraction which the earth exerts on a neighbouring mass. If the directions in which the magnetic forces are acting can be determined, it is possible to draw surfaces of *equal magnetic potential* round the magnet-pole.

In the diagram (Fig. 39) let N represent a single north-seeking pole of a magnet, and imagine a small north-seeking pole placed in a series of positions round N represented by the letter *n*. The force of repulsion will in each case act radially outwards, as shown by the arrows, and the surfaces of equal potential will be circles concentric with N. Work is required to be done to bring *n* from a distance to a position near N, therefore the potential energy of *n* is greatest when it is as near as possible to N. In other words, the space round N is *a region of magnetic potential*, which gradually diminishes in value as the distance from N increases.

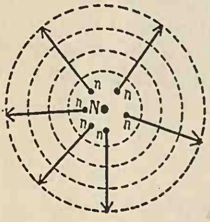


FIG. 39.—Surfaces of equal magnetic potential round a single magnet-pole.

If a small south-seeking pole be substituted for *n* then the direction of the forces is reversed, since *attraction* takes place instead of repulsion. Work must be done to remove the south-seeking pole from the region round N; consequently its *magnetic potential energy* will be greatest when it is *farthest* away from N.

Chief Points of Chapter IV

Force is that which tends to produce motion.

The Law of Gravitation.—Every particle in the universe attracts every other particle with a force acting in the direction of the line joining the two particles; the magnitude of this force is proportional to the product of the masses of the particles, and inversely proportional to the square of the distance between them. (Hence the force of gravitation obeys the so-called *Law of Inverse Squares.*)

Weight is the force of attraction which the earth exerts on any mass.

Units of Length.—(i.) *British.*—**The imperial yard** (=3 feet).
(ii.) *Metric.*—**The metre** ($=1\frac{1}{11}$ yard).
(iii.) *In scientific work.*—**The centimetre** ($=\frac{1}{100}$ metre).
(1 inch = 2.54 centimetres.)

Units of Mass.—(i.) *British.*—**The imperial pound avoirdupois.**
(ii.) *In scientific work.*—**The gram** (= the mass of 1 cubic centimetre of water at 4° C.).

$$(1 \text{ gram} = 15.43 \text{ grains} = \frac{15.43}{7000} \text{ pound avoirdupois.})$$

The Absolute Unit of Force is called the **Dyne**, and is equal to about the weight of $\frac{1}{1000}$ gram.

Parallelogram of Forces.—If two forces acting on a point be represented in magnitude and direction by the adjacent sides of a parallelogram, the resultant of these two forces will be represented in magnitude and direction by that diagonal of the parallelogram which passes through this point.

The Moment of a Force round any fixed point is equal to

$$\text{The magnitude of the force} \times \text{The perpendicular distance of the fixed point from the line of action of the force.}$$

A Couple is the term applied to two equal and parallel forces which are acting in opposite directions.

The Moment of a Couple is equal to one of the forces multiplied by the perpendicular distance between the two forces.

The Tangent of an angle is calculated by drawing a line perpendicular to one of the sides of the angle—the former is called *the perpendicular* and the latter *the base*.

$$\text{The tangent of the angle} = \frac{\text{the perpendicular}}{\text{the base}}.$$

The tangent of the angle of deflection is proportional to the deflecting force.

Work = Force overcome × Distance.

Power = Rate at which work is done.

The Energy of a body is its *capacity for doing work*. The energy is **Kinetic** if it is due to *actual motion* of the body, but **Potential** if due to the *position* of the body.

Other Forms of Energy.—*Heat*, *Magnetism*, *Electrification*, *Electric Currents*, and *Chemical Action*. These are mutually convertible.

Conservation of Energy.—Energy is never lost, but only changed in form.

A Surface of Equal Potential is one at all points of which the Potential Energy of a body will be the same. No work is done on a body in moving it from one point to another of such a surface; hence the surface must at any point be at right angles to the resultant force at that point.

Surfaces of Equal Gravitational Potential are imaginary spheres enveloping the earth, and concentric with it.

Surfaces of Equal Magnetic Potential round a single magnetic pole are spheres described round the pole as centre. If the pole is north-seeking the potential gradually diminishes in value as the distance increases; but if the pole is south-seeking the potential gradually increases with the distance.

Questions on Chapter IV

1. What is meant by Force? What are the results of the action of force upon a mass?

2. Describe fully any example of a mass which is at rest when acted upon by two forces.

3. Define the *mass* and *weight* of a material body.

4. Give the British units of mass and of length. Give also the units which are used in scientific work, and state the numerical relationship between the two sets of units.

5. State Newton's *Law of Gravitation*, and explain what is meant by *the Law of Inverse Squares*.

6. State the proposition known as the Parallelogram of Forces, and explain the terms *Resultant* and *Component Forces*.

7. The pole of a bar-magnet is held just over a piece of iron which it attracts with a force equal to 500 *dynes*. What is the least possible weight of the iron which will prevent the iron from being lifted?

8. What do you mean by the *moment of a force?* A thin magnet 20 cms. long is suspended horizontally by a thread, and a magnetic force equal to 20 dynes acts upon one of its poles at right angles to

the axis of the swinging magnet; what is the numerical value of the moment of the force?

9. Explain why a suspended magnetised needle swings to and fro several times before coming to rest when a bar-magnet is brought near to it.

10. Explain, with the aid of a diagram, how the principle of *Moments* determines the position in which a swinging magnet comes to rest when acted upon by two independent magnetic forces.

11. Explain clearly what is meant by *the tangent of an angle.* ABC is a triangle of which the angle ACB is a right angle; if AC = 40 millimetres, and BC = 20 millimetres, calculate the numerical values of the tangents of the angles ABC and BAC.

12. Define the terms *Work* and *Power.* Calculate the amount of work done, expressed in *absolute* units, when 1 gram is raised through a vertical distance of 10 centimetres.

13. What is the difference between Kinetic Energy and Potential Energy? Give a simple example of each.

14. Name some forms of energy, and give instances of the transformation of energy from one form to another.

15. Give instances to show that heat and chemical action are forms of energy.

16. State the principle of *Conservation of Energy.*

17. What is meant by a *Surface of Equal Potential?* How is the form of such a surface determined? Give an example of a surface of equal gravitational potential.

18. Represent by means of a diagram the form of the surfaces of Equal Magnetic Potential round a single south-seeking magnetic pole. In what part of the magnetic field will the magnetic potential of a single north-seeking pole be greatest?

CHAPTER V

MAGNETIC FIELDS

Apparatus required.—Bar-magnet. Compass-needle. Magnetometer. Long knitting-needle (40-50 cms. long). Metre scale. Drawing-board and sheet of paper.

A Field of Magnetic Force. — When a suspended magnetised needle is allowed to swing to and fro round its point of suspension, the manner in which it swings suggests that there are invisible forces acting on the needle which are similar in their action to a mechanical **Couple** (p. 38). Even when all artificial magnets and magnetic substances have been removed to a distance the needle swings in the same manner. Whenever these invisible magnetic forces appear to be influencing a suspended magnetised needle, it is said to be in *a field of magnetic force.* By observing the effects of such forces the presence of these forces is detected, and, in addition to this, their direction also is determined by observing the direction in which the needle points when it comes to rest.

Since the needle behaves in this manner even when no other magnet is near to it, the only possible conclusion is that *the earth itself must have a magnetic field of its own;* and if so, this must be due to a region of south-seeking magnetism situated in the direction of the north pole of the earth, and of north-seeking magnetism in the direction of the south pole. (See chapter on Earth's Magnetic Field.)

If a bar-magnet is held near to the swinging needle, a *magnetic disturbance* ensues which causes the needle to swing to and fro in the same characteristic manner, perhaps more rapidly, perhaps more slowly; and, in nearly every possible position of the magnet relatively to the needle, the needle

acquires a different position of rest. Evidently the bar-magnet has a field of magnetic force of its own, the effects of which have been superposed upon those due to the earth's field. The needle will come to rest in a position indicating the direction of the *resultant magnetic force* which is due partly to the bar-magnet and partly to the earth.

Again, it will have been observed that the needle swings sometimes rapidly, sometimes slowly. If it swings more rapidly, then the magnetic forces acting on it must be *stronger;* if it swings more slowly, the magnetic forces must be *weaker.*[1] In fact, by observing the rate of vibration, it is possible to compare the strengths of the magnetic forces at two different points.

Dr. Gilbert observed these effects, and described a lodestone or magnet as being surrounded by an "orb of virtue." About the middle of the present century Faraday substituted the term "magnetic field."

> EXPT. 36.—Place a bar-magnet on the table, and bring near to it a compass-needle, or a small magnetised needle suspended by a fibre. Move the needle into various positions relatively to the magnet, and observe the direction in which it points in each position. Observe also that when near to a pole of the magnet it swings rapidly, but when removed to a distance it swings slowly.

The Law of Inverse Squares.—The strength of the magnetic force which a bar-magnet exerts upon a compass-needle evidently depends upon their distance apart. This suggests a resemblance to the *law of inverse squares* which holds good with regard to gravitational forces: do magnetic forces obey the same law? Before proceeding to an experiment, it is necessary to consider the conditions under which it can be satisfactorily conducted. In the previous chapter it was proved that *the tangent of the angle of deflection is proportional to the deflecting force;* one of the forces remained constant throughout Experiment 35, while the other force acted in a direction at right angles to the first, and was varied in magnitude. The same conditions may be obtained in an experiment with magnetic forces by using the earth's magnetic force as the

[1] Compare Fig. 30.

constant force, and creating the variable force by means of a magnet placed at different distances from the compass-needle on which these forces may be made to act. If a bar-magnet is to be used, it is essential to remember that its poles will produce opposite effects, and the experiment only requires *one deflecting force;* hence steps must be taken to eliminate the effect of one pole of such a bar-magnet. All magnets have two poles, and there is no means of separating them bodily, so that the only possible course is to minimise the effect of one of them. Anticipating the result that the more distant the pole the less is its deflecting force, it is evidently necessary to use a very long magnet, so that one of the poles is too distant to exert an appreciable disturbing effect. The apparatus with which this experiment may be carried out is termed a *Magnetometer.*

The Magnetometer—EXPT. 37.—Fix a graduated circle (10 cms. diameter; divided into degrees, or, better still,

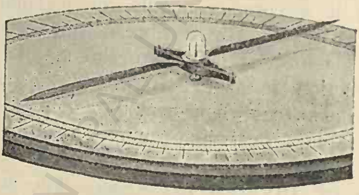


FIG. 40.—The needle of a magnetometer.

into divisions giving readings proportional to the tangent of angles of deflection) to a piece of stout millboard. Pass a short piece of sewing needle vertically through the centre of the scale. Fix the circle to the base-board of the magnetometer, and so that the zero-points of the scale coincide with the centre of the board. Cut the first 6 cms. from a wooden centimetre-scale, and fasten this along the middle of the base-board so as to measure exact distances from the centre of the circle. Fig. 40 represents a convenient form of magnetometer needle, which may be prepared from a short piece of glass tubing and two pieces (2 cms. long) of clock-spring, the

similar poles being bound together with copper wire. The pointer is made of thin aluminium foil, the strip on each side of the centre being bent into a vertical plane. A glass crystallising dish (11.5 cms. diameter, 6.5 cms. deep) serves as a suitable cover for the needle; or, instead of the dish, a shallow ring of cardboard may be used, on the top of which is laid a sheet of glass cut roughly to shape. The longer the deflecting magnet the more successful is the experiment (a magnetised knitting-needle about 45 cms. long is suitable). Adjust the board so that the wooden scale is perpendicular to the meridian, and lay the magnet along the scale with its near pole 15 cms. from the needle. Read the deflection of both ends of the pointer, and calculate the mean deflection. Repeat the observation with the magnet at various distances from the needle. Tabulate the results in the following manner:—

Distance.	Deflection (θ).	Tan θ.	(Distance)^2.	Tan $\theta \times$(distance)^2.
13	41°	0·87	169	147
15	33°·5	0·665	225	149
20	20°·6	0·3775	400	151
25	13°·6	0·2425	625	151
30	9°·7	0·17	900	153
35	7°·3	0·1275	1225	153
40	5°·6	0·097	1600	155
45	4°·3	0·075	2025	152

The experiment proves that magnetic forces do obey the Law of Inverse Squares; in other words, *the force which a magnet-pole exerts on a distant magnet varies inversely as the square of the distance.*

Note.—The use of a *long* magnet in this manner only diminishes the obvious source of error, and another method is frequently recommended which meets the difficulty; it is based upon the fact that if a magnet-pole is vertically over the centre of the compass-needle, it will exert no deflecting force. To ensure accurate verticality

requires carefully constructed apparatus. In order that the pole situated in the vertical plane may always be at a considerable distance from the compass-needle, the magnet should be at least 90 cms. long; if this pole is brought approximately near to the needle, the slightest error in verticality will produce a deflection of the needle which will ruin the experimental results.

The Poles of a Magnet.—In the experiment described in the previous section it was assumed that the magnetic forces originated from the extreme ends of the magnet. This assumption was sufficiently correct, owing to the fact that the

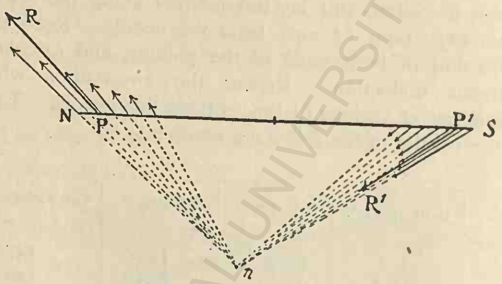


FIG. 41.—The points P and P′ are the poles of the magnet NS.

magnet was extremely long as compared with its width. If such a magnet be dipped into iron filings, the filings only adhere to the ends in a small compact bunch.

In the case of a comparatively short thick magnet, filings will adhere chiefly to the ends, but some adhere even at a considerable distance from the ends. The pole of the magnet would therefore appear not to be a well-defined point, but a superficial area of considerable extent, each portion of which exerts magnetic force on a neighbouring magnet. The polarity seems to be more pronounced at the ends, and to diminish gradually towards the middle of the magnet.

In Fig. 41 let NS represent a bar-magnet, and *n* a small single magnet-pole of north-seeking polarity. The pole *n* will repel all parts of the north-seeking end of NS with forces such as are represented in the figure—the portions nearer the extreme end being repelled more forcibly than others. Simi-

larly, n will attract all parts of the south-seeking end of NS. All the *repelling* forces may be imagined to be united into a single *resultant force* R acting at P, and the *attracting* forces united into a single *resultant force* R′ acting at P′. P *and* P′ *are the poles of* NS, and may be defined as *the points of application of the resultant forces of attraction and repulsion which the magnet exerts on any magnet-pole near to it.*

A small compass-needle placed near to a magnet always comes to rest pointing in the direction of the resultant magnetic force which is acting upon it. The position of the pole of a bar-magnet may therefore be determined by observing the direction of a compass-needle placed near to it.

EXPT. 38.—Lay a bar-magnet on a sheet of white paper stretched on a drawing-board, and mark its position by

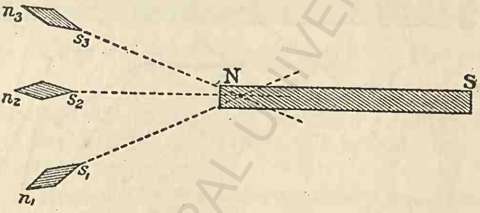


FIG. 42.—Experimental method of localising the pole of a magnet.

passing the point of a pencil round its edges (Fig. 42). Place a compass-needle at n_1s_1, and put pencil marks in line with its poles to indicate on the paper the direction in which it is pointing; repeat at n_2s_2 and n_3s_3. Remove the magnet, and produce by means of a straight edge the three directions obtained. The point of intersection of these lines indicates the position of the pole of the magnet.

It will be observed that the action of the other pole of the magnet has not been taken into account; this action will modify the direction of the compass-needle in all positions except n_2s_2, but its effect is minimised by placing the compass-needle at a considerable distance from S, in positions such as are shown in the diagram. To prevent any deflection of the compass-needle due to the earth's magnetic field, it is advis-

able to move the board round so that in each observation the needle is pointing directly towards the north; if this precaution is not taken the needle will point in the direction of the *resultant* force due to the combined action of the forces exerted by the earth's field and the magnet's field.

In short thick magnets (about 10 cms. long) the poles are situated about 1 cm. from each end. If the magnet is long, and only 1 or 2 millimetres wide, the poles approximately coincide with the ends.

Magnetic Forces due to both Poles of a Magnet.—So far, the theory of the magnetic field of a bar-magnet has

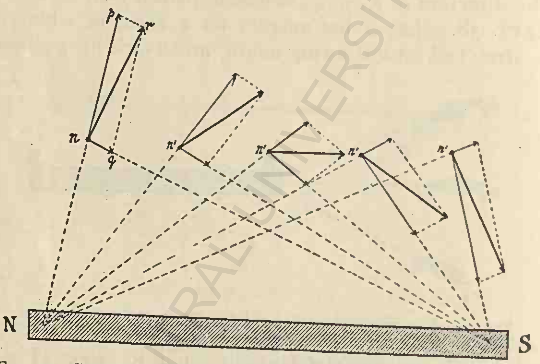


FIG. 43.—Graphical method of determining the magnetic forces due to a bar-magnet.

only been applied to the action of *one* pole of the magnet. The next step is to consider the forces due to *both* poles. Imagine, for simplicity, that a single north-seeking pole is situated at n near to a bar-magnet NS (Fig. 43); it will be repelled by N in the direction np, and attracted by S in the direction nq. Since these forces are inversely proportional to the square of the distance, np will be greater than nq, and in the ratio of $(nS)^2$ to $(nN)^2$. The resultant of these two forces is nr, and it is in the direction of this force that n will tend to move. The same method will determine the direction of the resultant force at other points, marked n', in the magnetic field.

It is an instructive exercise for the student to draw this diagram to scale on a sheet of paper, representing the magnet to be about 15 cms. long. The resultant forces

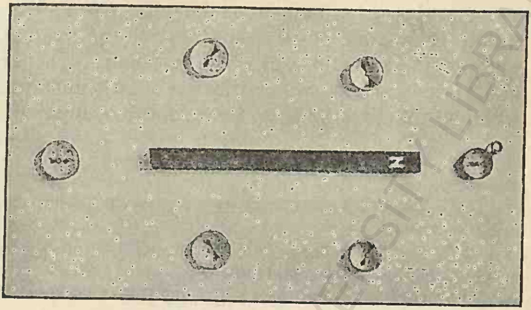


FIG. 44.—Experimental method of determining the relative directions of the forces due to a bar-magnet.

obtained will indicate not only their *relative directions*, but the lengths of the lines will indicate their *relative magnitudes* also.

If n is replaced by a *south-seeking pole* of equal strength to n, the forces due to NS will be equal in magnitude to those acting on n, but they will be *opposite in direction*. Consequently, if a *very short* compass-needle is placed at the point n, it will not tend to travel bodily in any direction, since the forces acting upon it are equal and opposite, but it will simply come to rest pointing in the direction nr; at n' it will point in the direction of the resultant force at that point.

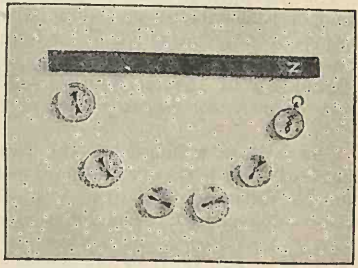


FIG. 45.—To illustrate Expt. 39.

The earth's magnetic field will modify the direction of the needle to a greater or less extent. In the near neighbourhood

of the magnet the force due to the earth's field will be small in comparison to that due to the magnet, but at greater distances it will have more influence since the force due to the magnet will be considerably less than at points nearer to it.

EXPT. 39.—Lay a bar-magnet on the table, place a compass-needle in a series of positions near to the magnet, and observe the directions in which it points. In Figs. 44 and 45 several compass-needles are used simultaneously, whereby the directions are more clearly compared.

CHIEF POINTS OF CHAPTER V

A Field of Magnetic Force is any region in which magnetic force can be detected.

If a compass-needle tends to come to rest pointing in one definite direction, there must be a magnetic force causing it to do so. Hence a compass-needle serves as a means of investigating whether magnetic force is present or absent.

The Earth itself has a magnetic field of its own; so also has every artificial magnet.

The Direction of the Magnetic Force at any point is indicated by the direction in which a compass-needle comes to rest. If the needle is acted upon by force in more than one direction, then its final position of rest indicates the direction of the **Resultant Magnetic Force.**

The Strength of the Magnetic Force.—The rate at which a compass-needle vibrates to and fro when placed in a magnetic field depends upon the magnitude of the force acting on the needle. In a stronger field the needle vibrates more rapidly.

The Law of Inverse Squares.—*The Force which a magnet-pole exerts on a distant magnet-pole varies inversely as the square of the distance.*

The Pole of a Magnet.—The part of a magnet to which iron filings will cling is not a well-defined point, but rather an area of considerable extent, each portion of which exerts magnetic force on a neighbouring magnet. **The Poles** may be accurately defined as *the points of application of the resultant forces of attraction and repulsion which the magnet exerts on any magnet placed near to it.*

The Magnetic Field round a bar-magnet is the Resultant of the two separate fields of magnetic force due to the two poles of the magnet.

QUESTIONS ON CHAPTER V

1. Explain, with the aid of a diagram, the behaviour of a compass-needle when acted upon by magnetic forces in the form of a *couple.*

2. What is meant by a Field of Magnetic Force? How can it be detected?

3. To what extent does a compass-needle give us information as to (*a*) the direction, (*b*) the magnitude of the forces in a magnetic field?

4. How would you experimentally prove that the direction and magnitude of the forces in the magnetic field of a bar-magnet are not the same at all points?

5. State the Law of Inverse Squares as applied to magnetic forces.

6. Describe a simple experiment which you would carry out in order to prove the law of inverse squares.

7. A compass-needle is supported on a cork floating on water, and a bar-magnet is held with its axis in line with that of the compass-needle. Explain why the compass-needle is bodily drawn towards the pole of the bar-magnet.

8. Explain why the result of the experiment described in Question 7 is more marked when a long bar-magnet is used instead of a short one (assuming that the magnetic strength of the long and short magnets is the same).

9. Define accurately what is meant by the Pole of a Magnet. Describe a simple method of locating the poles of a magnet, mentioning any special precaution which it is advisable to take.

10. Explain how it is possible to calculate, with the aid of a diagram, the direction of the magnetic force in the field of a bar-magnet. How would you experimentally verify the calculated results?

11. A magnetised steel rod is placed at a considerable distance from a compass and produces a certain deviation of the needle. The rod is then broken in two, and one of the halves is placed in the same position as before. Will the deviation of the compass be less or greater than before? Give reasons for your answer. (1895.)

CHAPTER VI

MAPS OF MAGNETIC FIELDS

Apparatus required.—Imperial drawing-board and sheets of paper. Compass-needle. Bar-magnets and horse-shoe magnet. Sheets of paraffined paper. Bunsen-burner. Sewing-needles. Silk fibre. Compass-needle with brass pointer perpendicular to the axis of needle.

In order to investigate the character of any magnetic field, it is necessary to determine two factors at all parts of the field—(i.) *the direction of the magnetic force*, and (ii.) *the strength of the force.* The present section is devoted to the methods of determining the *direction* of the forces. Any diagram which represents these *force-directions* is termed *a map of the magnetic field* included within the area of the diagram. An accurate method of obtaining such maps is based upon the fact that a compass-needle, when swinging freely in a horizontal plane, will point in the direction in which the magnetic forces are acting.

Map of the Earth's Magnetic Field. EXPT. 40.—Fasten a square sheet of white paper (80 cms. × 60 cms.) on a table, with one edge pointing approximately north and south. Mark off one of the edges pointing east and west into spaces about 5 cms. wide. Place a sensitive compass-needle so that one of its poles is just over one of the marks, and indicate by means of a pencil mark the direction in which the other pole is pointing. Move the needle until its first pole is exactly over the second pencil mark; continue this process of marking the directions of the compass-needle until a series of marks have been obtained completely across the paper. Join up

these points by a continuous pencil line. Plot out other lines in a similar manner, in each case starting from one of the equidistant pencil marks at the edge of the paper. Indicate by means of arrow-heads the direction in which the north-seeking pole of the compass-needle *tends* to move; this is called *the positive direction of the magnetic field.*

The diagram obtained is a *horizontal* map of the earth's magnetic field, so far as the limits of the paper will allow. Faraday, in 1837, termed the lines so obtained *lines of magnetic force*, *i.e.* lines which indicate the direction in which the magnetic forces are acting.

This map indicates that the lines of magnetic force due to the earth are uniformly parallel straight lines. The same result would be obtained if the experiment were conducted in any other part of the room. Hence it may be stated that the earth's magnetic field is uniform over an area much larger than is required for the carrying out of ordinary experiments in magnetism.

Care must be taken that there are no iron pipes or rods just under the table, which might affect the direction of the compass-needle.

Maps of the combined Magnetic Fields due to a Bar-Magnet and the Earth

In a previous section (p. 60) a method was described by which it is possible to calculate the direction of the magnetic force due to a bar-magnet alone. In actual experiments the map really obtained is one which represents the combined magnetic forces of the magnet and of the earth. In regions near to the magnet the forces due to the earth are almost negligible as compared with those due to the magnet; thus, if nr (Fig. 46, i.) represents the resultant force due to the two poles of the magnet acting on a single north-seeking pole at n, and nE represents the force due to the earth, then nR will represent the final resultant force, and therefore the direction in which a compass-needle will point. The angular *distortion* from nr to nR is comparatively small. At greater distances from the magnet nr becomes less (Fig. 46, ii.), while nE has

the same magnitude as before. The direction of nR indicates that the distortion due to the earth is more pronounced. At still greater distances nr becomes almost negligible, and the compass-needle obeys the force due to the earth alone.

EXPT. 41.—Fasten a sheet of paper on the table in the same manner as in Expt. 40. Determine accurately

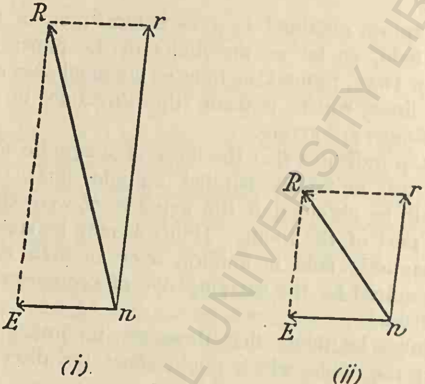


FIG. 46.—The effect of the earth's field becomes more evident when the forces due to the magnet are weaker.

the north and south line by the compass-needle, and place a bar-magnet at the centre of the paper with its axis pointing north and south. Starting from a series of equidistant points marked along the top edge, map out the lines of force in the same way as before.

(i.) *With the north-seeking pole of the magnet pointing towards the south* (Fig. 47).—Observe that the lines of force near to the magnet appear to emerge from the north-seeking pole, tracing out a curved path and re-entering the magnet at its south-seeking pole. At greater distances the lines of force appear to be those due to the earth, which have been distorted by the presence of the magnet. Also observe that there are two regions (*marked* X) in which the magnet's effect is exactly neutralised by that of the earth, and in which the needle will consequently come to rest in any position with

equal readiness; these regions are termed *neutral points.*

(ii.) *With the south-seeking pole of the magnet pointing towards the south* (Fig. 48).—Observe how the lines of force due to the earth appear to be drawn together by the

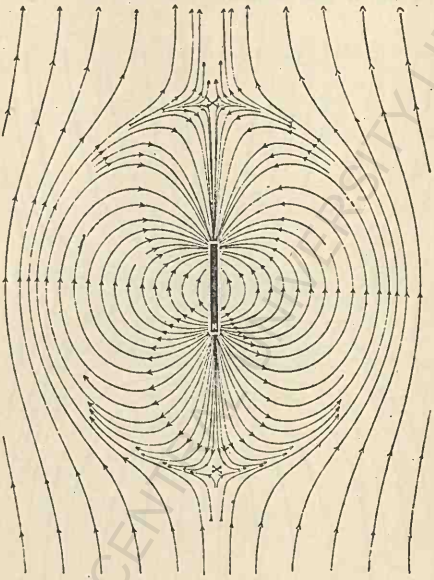


FIG. 47.—Map of the combined field due to the earth and a bar-magnet (N pole pointing south).

magnet, and how the more distant lines are distorted. The neutral points are now east and west of the magnet.

(iii.) *With the axis of the magnet lying east and west* (Fig. 49).—Again the earth's lines of force appear to be drawn together by the magnet. If the lines are followed in the positive direction, they appear to proceed from the south towards the south-seeking pole of the magnet, to emerge at the north-seeking pole, thence spreading outwards towards the north.

(iv.) *Magnetic Field due to a bar-magnet alone.*—In order to eliminate the magnetic forces due to the earth, it is necessary to move the drawing-board on which the experiment is conducted before each observation of the compass-needle's direction, so that it always points exactly north and south. The earth's magnetic forces

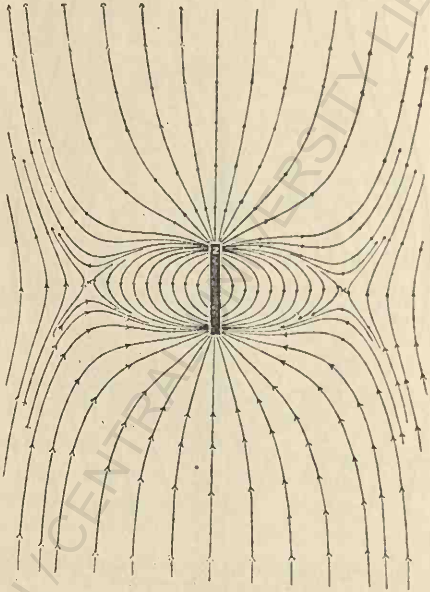


FIG. 48.—Map of the combined field due to the earth and a bar-magnet (N pole pointing north).

will, in such a case, have no tendency to deflect the needle from the position which it will occupy in obedience to the forces due to the bar-magnet alone; referring to Fig. 46, it will be clear that, when the experiment is conducted in this manner, the directions of nr and nE will always coincide, and consequently the resultant force nR will also be in the same direction.

Characteristics of the Lines of Force.—From the maps so obtained, it is evident that the lines of force never cross each other, nor do they actually unite. Each line of force appears to have a perfectly independent course of its own. It is also evident that the lines always proceed in the

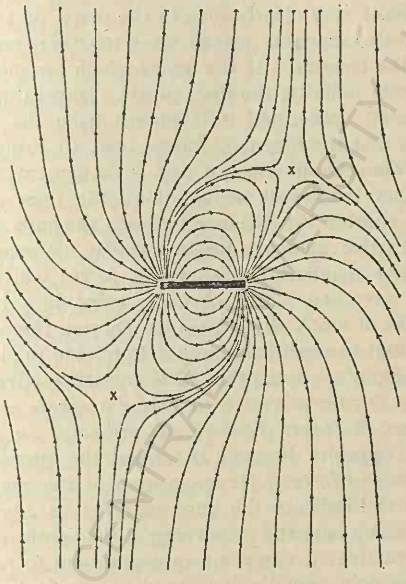


FIG. 49.—Map of the combined field due to the earth and a bar-magnet (pointing east and west).

positive direction from regions of north-seeking polarity to a region of south-seeking polarity, and in no case do they directly connect regions of similar polarity. In these maps the lines originate from a region of north-seeking polarity, which we already know to exist towards the south geographical pole; under ordinary conditions they proceed directly to a region of south-seeking polarity situated near to the north geographical pole. But if the south-seeking pole of a magnet intervene, the lines proceeding near to the magnet are drawn towards it, and

emerge again to connect the north-seeking pole with the earth's south-seeking polarity towards the north.

Where the lines of force due to a magnet and the lines due to the earth are on the same errand (*e.g.* both proceeding towards a region of south-seeking polarity), they appear to repel one another, but if on different errands they unite together freely. This is very clearly seen in the maps of the magnetic field due to two magnets placed close together, reproduced at the end of the chapter. If the poles which are close together are of opposite polarity, the lines of force travel directly across the intervening space, and it is known from the preliminary experiments that the magnetic forces tend to bring the poles together. The examination of any arrangement of magnets will show that the forces acting along the lines are such as will tend to shorten the distance between the ends of the lines. A very instructive analogy, due to Faraday, compares the properties of the magnetic lines to the forces which would be exerted by stretched elastic threads, coinciding in direction with the lines of force, which tend to shorten themselves from end to end and to repel one another from side to side.

It is generally accepted that **the positive direction** *of a line of force is that direction in which a single north-seeking pole will tend to travel if placed at any point on that line of force.* The opposite direction is termed the **negative** direction of the line of force. Hence, a map of the magnetic field of a magnet will indicate the lines of force as *emerging* from the north-seeking pole and *re-entering* at the south-seeking pole.

It is instructive to carry out an experiment to prove that a north-seeking pole actually does tend to travel along a line of force in the positive direction.

EXPT. 42.—Support a bar-magnet, 20 cms. long, near and parallel to the edge of a large photographic dish filled with water. Magnetise a short fragment of sewing-needle, and fix it through a small piece of cork so that the needle can float freely in a vertical position. Let the north-seeking pole of the needle be uppermost. If floated near to the north-seeking pole of the magnet the repulsion of the similar pole of the needle will be stronger than the attraction of the opposite pole of the needle, since the latter is more distant. The needle will

slowly travel over the surface of the water, tracing out a curved path connecting the north- and south-seeking poles of the magnet.

Other Methods of obtaining Maps of Magnetic Fields.—The compass-needle method, already described, has the advantage of accuracy, and it is also capable of affording information in parts of a magnetic field which would be too weak to be mapped out by the methods now to be described. The latter will give accurate maps of the field *near* to a magnet, but will not do so for the more distant parts where the earth's magnetic field is predominant. The compass-needle method, however, cannot well be adopted in the lecture-room owing to the time required to obtain even one complete map.

The more rapid methods depend upon the principle of magnetic induction whereby a piece of soft iron, when placed in a magnetic field, becomes magnetised by induction. Soft iron filings may be used for the purpose; each fragment will become a temporary magnet, and, if free to move, will behave in the same manner as a compass-needle. The effect is approximately the same as would be obtained if an extremely large number of compass-needles had been used, and, moreover, the general contour of the whole field is visible simultaneously.

Figs. 50-58 have been mostly reproduced from permanent maps obtained by using "*photographic paper*"[1] instead of ordinary paper. A piece of the paper is laid over the magnet, or magnets, and is supported horizontally on pieces of wood of the same depth as the magnet, and placed on either side. The whole arrangement is supported on a drawing-board to enable the experiment to be placed in the brightest daylight available; it is advisable to pin the paper down at the edges. Iron filings contained in a muslin bag (or a pepper-box) are uniformly sprinkled over the paper, which is then tapped gently with a pencil or a copper wire so as to give the necessary freedom of movement to the filings. The paper is then exposed to bright daylight for several hours, care being taken not to disturb the filings. The paper is developed by washing in running water for an hour.

[1] Photographic paper giving black lines on white background can be obtained from Mr. Thornton, St. Mary's Street, Deansgate, Manchester.

For class purposes another method of obtaining permanent maps is, since the photographic method requires prolonged exposure, to be preferred. Paraffin wax is melted in a large flat dish or shallow tin, sufficiently large to take half a sheet of foolscap paper. A sheet of thin white paper is passed once through the melted wax, and held vertically until the wax on the paper has solidified; several more sheets are prepared in the same

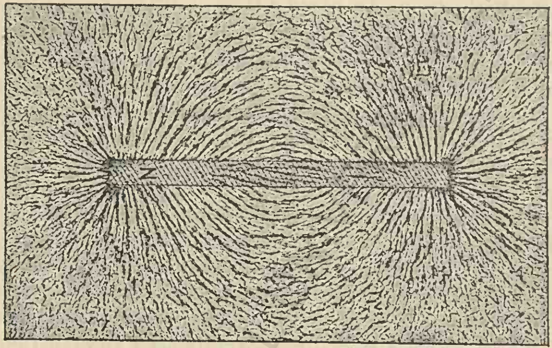


FIG. 50.

way. In preparing a map of the magnetic field, the filings are sprinkled over the paraffined paper, and are fixed in position by passing a Bunsen flame over the surface until the wax has melted slightly; when cold, the filings are firmly fixed to the paper.[1]

[1] A more suitable method of demonstrating fields of force to large classes is possible if a lantern with horizontal projection appliance is available. The magnets are made from short pieces of narrow clock-spring, about 2 cms. long, and are fixed with wax to the under side of plain lantern-slide glasses. The poles are distinguished by painting the glass near to them with transparent colours—north-seeking poles are painted red and south-seeking poles blue. (The colours may be conveniently made by mixing dry colours or aniline dye stuffs with water, to which a little sugar has been previously added.) The glass slides are placed on the horizontal carrier with the magnets underneath, filings are sprinkled over the upper surface, and the glass is gently tapped to allow the filings to arrange themselves.

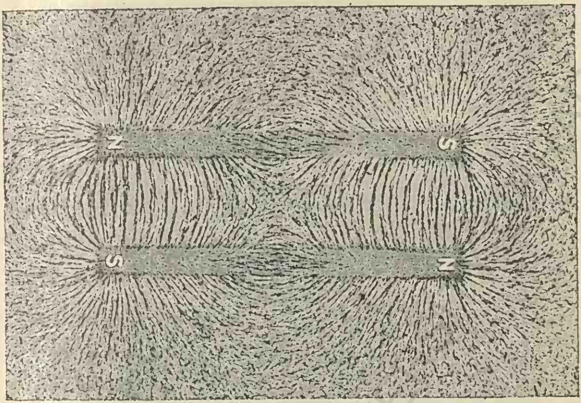


FIG. 51.

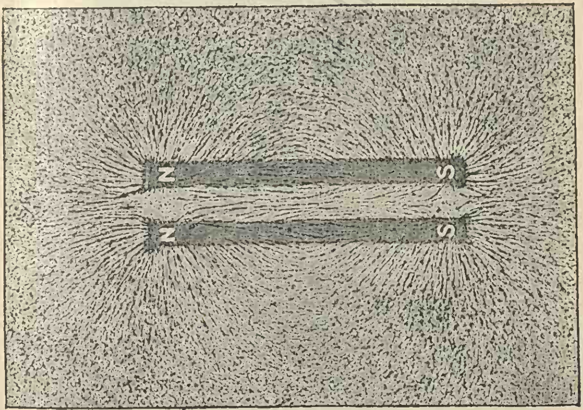


FIG. 52.

EXPT. 43.—Obtain maps of the magnetic fields due to the following arrangements of magnets :—

(i.) *One bar-magnet* (Fig. 50).

(ii.) *Two bar-magnets side by side, with unlike poles together* (Fig. 51).

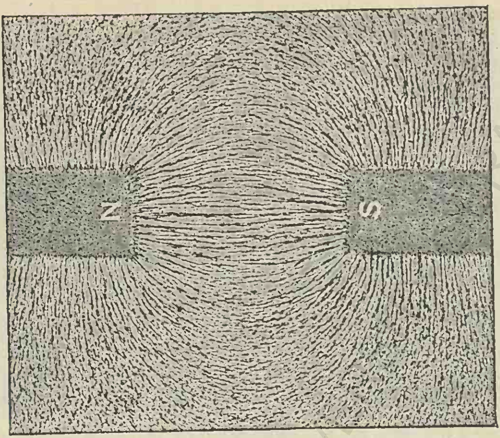


FIG. 53.

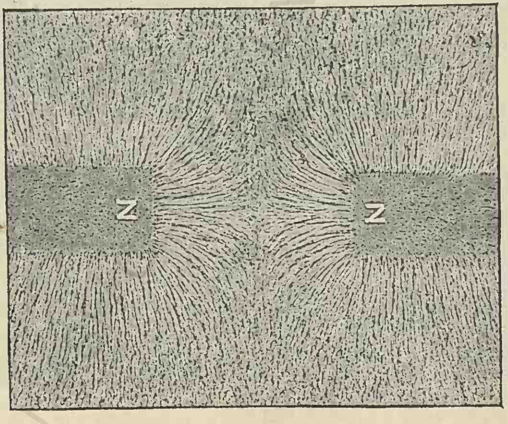


FIG. 54.

(iii.) *Two bar-magnets side by side, with like poles together* (Fig. 52).

(iv.) *Two bar-magnets, with their axes in line, and unlike poles together* (Fig. 53).

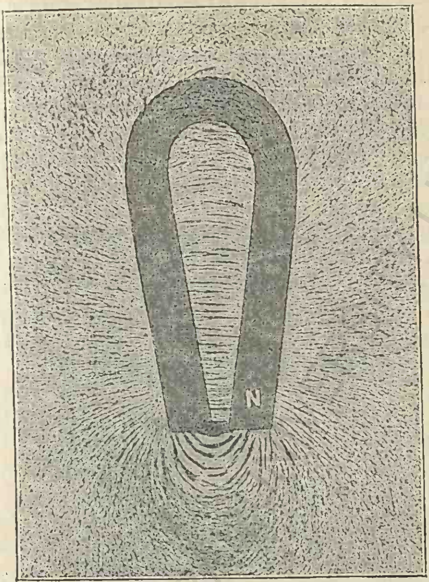


FIG. 55.

(v.) *Two bar-magnets, with their axes in line, and like poles together* (Fig. 54).

(vi.) *One horse - shoe magnet, without keeper* (Fig. 55).

(vii.) *One cylindrical bar-magnet, fixed in a vertical position, and the paper supported horizontally over the upper pole* (Fig. 56).

(viii.) *Two bar-magnets at right angles to each other, the axis of one passing through the middle point of the other* (Fig. 57).

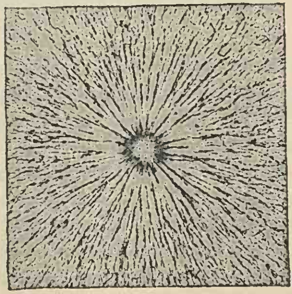


FIG. 56.

The Cause of the vacant Spaces in Figs. 52, 55, and 56.—In some cases these maps indicate small areas which are quite free from iron filings, and the student is apt to think that this is due to the absence of magnetic force, and that the space is similar to the *neutral points* determined by the compass-needle method. The freedom from filings is due to the magnetic forces being so great that the filings are drawn bodily towards the poles of the magnet, where they accumulate in considerable

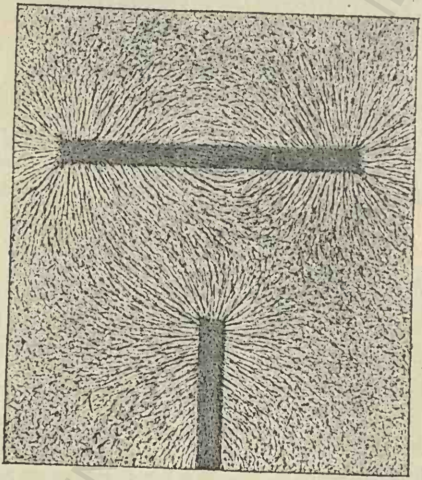


FIG. 57.

quantity; hence a clear space indicates maximum, rather than minimum, magnetic force. Regions of minimum magnetic force are indicated by the filings lying uniformly over the paper and in a higgledy-piggledy manner.

Symmetry of the Magnetic Field duo to a single Bar-Magnet.—In Fig. 50 it will be seen that lines of force emerge from and re-enter the magnet at all points (with the exception of a small portion near to the centre), and the distribution of the lines is densest in parts near to the extreme ends. The map does not indicate those lines of force which pass vertically through the paper, nor those which pass

vertically downwards through the table; in fact, the map is really a horizontal cross-section through the magnetic field. If it were possible to obtain a *vertical* map by the same methods, it would be found that the arrangement of the lines of force is identical with that obtained in the horizontal maps. If the magnet is turned over on to its side the lines of force which were originally in a vertical plane will now be horizontal, and a map of the field of the magnet in this position will show that their contour and general distribution is identical with that obtained when the magnet was in its original position. The lines of force in a vertical plane can readily be detected by means of a short magnetised needle supported from its centre by a silk fibre.

EXPT. 44.—Attach a silk fibre to a small sewing-needle and adjust the fibre so that the needle is exactly horizontal when swinging freely. Magnetise the needle by placing it inside a spiral of wire through which an electric current is passing. Clamp a large bar-magnet in a horizontal position and support the needle vertically over and under the magnet in a series of different positions (Fig. 58).

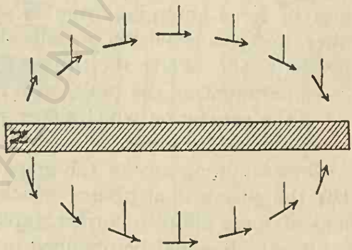


FIG. 58.—The vertical field of a bar-magnet mapped out by means of a suspended magnetised needle.

It will be evident that the general contour of the vertical magnetic field is the same as the horizontal.

In fact, *the distribution of the lines of force is the same in all planes besides the horizontal and vertical.* A bar-magnet may be imagined to be completely clothed on all sides in an invisible garment of lines of force.

Resultant Magnetic Fields.—The symmetrical distribution of lines of force is disturbed when another magnet (or any magnetic substance) is placed within the field, and the nature of the disturbance can be judged with fair accuracy by remembering the chief characteristics of the lines

of force. For example, in Fig. 51 many of the lines of force emerging from N *take the shorter path to* the south-seeking pole of the neighbouring magnet; the lines of force on the distant side of N become less evident, and the magnetic forces on that side are considerably diminished. The space between the two magnets is crowded with lines of force which, *in their tendency to shorten*, will draw the magnets together if these are free to move.

EXPT. 45.—Magnetise two sewing-needles and lay them on a smooth table in the same relative positions as shown in map ii. (Fig. 51). The needles immediately roll towards each other, and remain in contact. The same effect may be obtained with two cylindrical magnets.

In Fig. 52 the magnetic field between the magnets is weakened, while it is strengthened on the distant side. The lines of force emerging from N and N appear to repel each other, and this repulsion actually does take place.

EXPT. 46.—Place the two needles used in the previous experiment on the table, with like poles together; observe the separation which takes place as soon as the needles are free to move.

On examining any of the maps the student will clearly see that the physical attributes which Faraday has given to the lines of force afford a correct explanation of the experimental results which would be obtained in each case.

The character of the disturbance in a magnetic field, as determined by considering the lines of force, may be verified by applying the *law of inverse squares*—the method which was adopted on p. 60—and determining at various points what change, if any, in the magnitude of the forces acting on a single magnet-pole will result from the disturbance.

The *disturbance* is, in reality, due to the fact that there are two independent fields of magnetic force which overlap one another; and the map which is obtained by experiment is the single *resultant* field due to the fields which overlap.

A careful consideration of the distribution of the lines of force in any arrangement of magnets will always afford a

correct conclusion as to the actual result which would be obtained in an experiment. It is always advisable to make a careful diagram, sketching in a *few* of the more important lines of force, before forming an opinion as to the possible experimental results.

Surfaces of equal Magnetic Potential.—These surfaces have already been referred to in Chapter IV. The student will remember that work must be done *on*, or *by*, a magnet-pole if it passes from any equipotential surface to a neighbouring one; also *no work* is done when a magnet-pole is moved *along* an equipotential surface.

A map of these surfaces may be obtained in the same manner as described on p. 64, by using a compass-needle which has a short brass cross-bar fixed at right angles to its axis, and mapping out the directions of the cross-bar instead of that of the needle.[1]

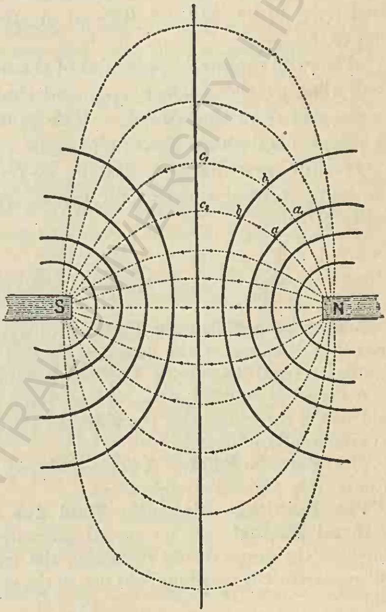


FIG. 59.—The thick lines indicate surfaces of equal magnetic potential.

EXPT. 47.—Place two bar-magnets on a sheet of paper with their axes in line, and with unlike poles about 10 cms. apart (as shown in Fig. 59). Map out about seven or eight *lines of force* by means of the needle, and the same number of *surfaces of equal potential* by means of the *cross-bar*. The former are

[1] An excellent compass-needle of this pattern may be obtained from Mr. W. Groves, Bolsover Street, W.

represented in the figure by dotted lines, and the latter by continuous lines.

The work required to move a single north-seeking pole from c_1 to b_1 is the same as that required to move it from c_2 to b_2; or,

$$\text{Force}_1 \times \text{Distance } c_1b_1 = \text{Force}_2 \times \text{Distance } c_2b_2.$$

Since c_1b_1 is greater than c_2b_2, Force_1 must be *less* than Force_2. This would be anticipated by remembering that the magnetic force will be less at a greater distance from the magnets.

Also, the magnetic potential of the surface b_1b_2 will be greater than that of the surface c_1c_2, and that of the surface a_1a_2 will be greater than that of b_1b_2. The potential gradually increases as we proceed along the line of force $c_1b_1a_1$ from S towards N.[1]

If time permits, the student is recommended to map out the equipotential surfaces for other arrangements of magnetic fields of force.

Chief Points of Chapter VI

A Map of a Magnetic Field is a diagram indicating, by means of lines, the direction of the magnetic force at various points of the field. Faraday termed these lines *Magnetic Lines of Force.*

A map only indicates the lines of force in that cross-section of the field which coincides with the plane of the paper on which the map is experimentally obtained.

The Earth's Field.—A horizontal map of the earth's field consists of uniformly parallel straight lines.

The Resultant Magnetic Field due to the Earth and to an artificial Magnet.—If no special precautions are adopted in order to eliminate the forces due to the earth, the map obtained experimentally will represent the resultant field due to the earth's field and the magnet's field.

The forces due to the magnet at points near to it are, as a rule, great as compared with those due to the earth. In such regions the map will be a slightly distorted representation of the magnet's field. At considerable distances from the magnet the map will be a distorted representation of the earth's field.

Points at which the two fields exactly neutralise each other are termed *the neutral points.*

Such maps may be experimentally obtained by two methods—(i.)

[1] The potential of a single *north*-seeking pole is always chosen in order to express the magnetic potential at any point.

the compass-needle method, (ii.) *the iron-filings method.* In the latter method, the extent of the area of a magnet's field which can be mapped out is restricted to regions quite near to the magnet, and scarcely extends to those regions in which the distortion due to the earth's field becomes apparent.

Maps of Magnetic Fields due to a Magnet alone.—The effect of the earth's field may be eliminated by adjusting the experiment at each step so that the compass-needle always comes to rest in the magnetic meridian.

Properties of Lines of Force.—Lines of force always proceed between regions of unlike polarity, and never proceed between regions of like polarity.

Faraday has compared lines of force to stretched elastic threads which tend to shorten and to repel one another from side to side. As a result of this hypothesis, the lines of force will always tend to take the shortest possible path between regions of opposite polarity, so far as their tendency to mutual repulsion will allow.

The Positive Direction of a Line of Force is that direction in which a single north-seeking pole will tend to travel if placed at any point on that line of force.

Symmetry of a single Bar-Magnet's Field.—The lines of force due to a single bar-magnet are symmetrically distributed in the space round a bar-magnet, and their distribution will have the same character from whatever point the magnet is viewed.

Surfaces of Equal Magnetic Potential in a magnetic field are always perpendicular to the lines of force. No work is done when a magnet-pole passes along such a surface. Although the distance between two consecutive surfaces may not be the same at all points, yet the work done in carrying a magnet-pole from one to the other will always be the same.

QUESTIONS ON CHAPTER VI

1. A bar-magnet lies on a table; on it is placed a piece of cardboard on which iron filings are lightly scattered; on the cardboard being gently tapped the iron filings lie in certain lines. Sketch the general appearance of these lines, and explain why they are formed.
(C. U. L. Senr., 1889.)

2. A strong bar-magnet is set upright, and a sheet of cardboard rests horizontally on the top of it. Describe and show by a sketch the way in which iron filings sprinkled on the cardboard arrange themselves. (1881.)

3. Three precisely similar magnets are placed vertically, with their lower ends on a horizontal table. Iron filings are scattered over a plate of glass which rests on their upper ends, two of which are north

poles and the third a south pole. Give a diagram showing the forms of the lines of force mapped out by the filings. (1889.)

4. Several bar-magnets are placed on a table. How would you use a card and iron filings to determine how to place a nail, lying horizontally on the table with its centre at a given point, so that it may acquire (i.) the largest, (ii.) the smallest possible amount of magnetism by induction? (1892.)

5. Two bar-magnets are laid on a table at right angles to each other, so that the axis of one passes through the middle point of the other. They do not touch. A sheet of cardboard over which iron filings are uniformly scattered is placed over them and tapped. Draw a picture showing the appearance which the iron filings present. (1892.)

6. A strong bar-magnet is placed on a table with its axis lying in the magnetic meridian, and with its north-seeking pole towards the north. State in what direction a compass-needle points (i.) when placed immediately over the centre of the magnet, (ii.) when gradually raised vertically upwards. (1888.)

7. Describe and explain an experimental method of obtaining a horizontal map of the earth's magnetic field. Show by means of a sketch the general character of the map.

8. Explain what is meant by the term *Resultant Magnetic Field*, and give a diagram of an example.

9. Explain what is meant by the *Neutral Points* in a resultant magnetic field. How can they be located experimentally?

10. Define the *Positive and Negative Directions of a Line of Force*. Describe an experiment which you would carry out in order to exemplify your definitions.

11. What characteristic property of a line of force determines the direction in which lines of force traverse the intervening space between regions of magnetic polarity? What physical property can be attributed to lines of force in order to explain the relative movements of two regions of magnetic polarity which are free to move? Give diagrams to explain your answers.

12. Describe briefly what is meant by a *Surface of Equal Magnetic Potential*. Make a rough diagram of the surfaces between two magnet-poles of opposite polarity.

13. What is meant by a line of force? Draw diagrams showing the general form of the lines of force when a small magnet is placed with its axis parallel to the lines of force of the earth's field if the north pole of the magnet is turned towards (1) the north, and (2) the south. (1903.)

CHAPTER VII

INTERNAL MAGNETIC FIELDS—WEBER'S THEORY —MAGNETIC SCREENING

Apparatus required.—Bar-magnets. Several compass-needles. Clock-spring. Sheets of paper. Iron filings. Glass test-tube and steel filings. Darning-needles. Soft iron bar and slab. Magnetometer needle.

Internal Magnetic Fields.—So far, only the magnetic phenomena in the region *round* a magnet have been considered. Does each line of force have two free ends situated at the points where it leaves and re-enters the magnet? or does each line continue through the substance of the magnet, and so form a complete loop without any free ends? To answer these questions we cannot, it is clear, introduce a test-needle into the interior of the magnet; but it might be possible to cut out a small piece of the magnet sufficiently large to insert a test-needle. It is, however, much easier to break the magnet completely through, and then separate the broken ends slightly, so as to expose any lines of force which may be present.

EXPT. 48.—Magnetise a piece of clock-spring about 10 cms. long. Break it into halves. Examine the pieces by a compass-needle. One half does not possess north-seeking polarity only, and the other half south-seeking polarity; each half is in itself a complete magnet, possessing two unlike poles. Lay the halves on the table in line with one another, and about 2 cms. apart. Sprinkle iron filings on to a sheet of paper placed over the clock-springs; there are evidently lines of force connecting the broken ends. Break the spring

into still smaller fragments, and test the polarity of each. Observe that the like poles of every fragment point in the same direction.

Evidently the lines of force traverse the length of the magnet, and each small fragment is traversed to a greater or less degree by lines of force, which enter at its south-seeking pole and emerge at its north-seeking pole (Fig. 60).

Since each small fragment is a complete magnet in itself, a bar-magnet may be regarded as consisting of a large number of minute magnets arranged with like poles pointing in the same direction. There is no theoretical reason why this

FIG. 60.—A broken magnet.

breaking process should not be continued until the fragments are almost infinitely small, and each such fragment found to be still a complete magnet. Modern theory maintains that even the smallest physical quantity—the *molecule*—present in a bar-magnet is a minute magnet, though the bar may contain several millions of such molecules.

Do the molecules become magnetised simultaneously with the magnetisation of the magnet? or do they naturally possess a polarity which only becomes evident externally after the bar has been magnetised?

EXPT. 49.—Fill a glass test-tube with steel filings loosely packed; cork up the tube, and notice that it behaves towards a test-needle like an ordinary piece of iron. Magnetise the tube by single touch, or better, by means of a spiral of wire and electric current (Expt. 14). Observe that the tube now has opposite polarities at the two ends, and that the filings appear to some extent to have arranged themselves lengthwise. Each filing has been magnetised, just as small sewing-needles would have been magnetised by similar treatment. Each filing has its lines of magnetic force, which come from, and afterwards pass into, neighbouring filings, and which only appear at the ends of the tube where they emerge

into the surrounding space. Empty the filings out on to a sheet of paper, mix well together, and pour them back into the tube; again test for polarity.

The polarity has been destroyed, and the tube again behaves like an ordinary piece of iron. The filings cannot have been demagnetised by merely mixing them; is it possible that their magnetism is simply *hidden* within the tube? Can the magnetism of one filing be masked by that of a neighbouring filing?

FIG. 61.—Two magnets forming a closed magnetic chain.

EXPT. 50.—Place two equally-magnetised darning-needles side by side, with unlike poles together. Take a map of the magnetic field with iron filings. Observe the behaviour of a compass-needle at various points in the neighbourhood.

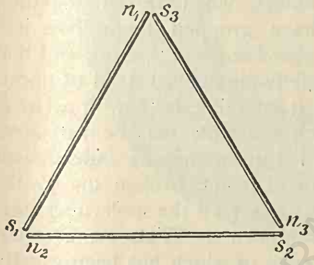


FIG. 62.—Three magnets forming a closed magnetic chain.

The external magnetic forces of each magnet have disappeared; all the lines of force emerging from N_1 (Fig. 61) are drawn towards S_2, and those of N_2 are drawn towards S_1. The magnetic forces are concentrated into the small regions N_1S_2 and N_2S_1. At a distance the whole arrangement behaves like a mass of unmagnetised iron.

EXPT. 51.—Show that the external magnetic forces of three similar magnets would neutralise each other if arranged as shown in Fig. 62.

Each line of force traverses the sides of the triangle taken in order, and no lines are found externally. Any such arrangement is termed a **closed magnetic chain.**

If the three magnets are arranged like three sides of a square, as shown in Fig. 63, then the arrangement is termed an **open magnetic chain,** and an external magnetic field of force exists in the space between n_1 and s_3.

The most perfect example of a closed magnetic chain is *an iron ring* which is magnetised along the curved axis of the iron (Fig. 64). The magnetic field is completely internal, and its presence can only be detected by cutting a small gap in the ring sufficiently large to introduce a test-needle.

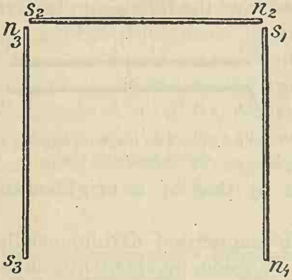


FIG. 63.—An open magnetic chain.

Returning to Expt. 49, it is evident that the disappearance of the external magnetic field round the tube of iron filings may be due to the fact that the filings, when mixed together, have grouped themselves into *closed magnetic chains*, and that the general arrangement is higgledy-piggledy instead of linear.

Weber's Theory.—The next inference is that, in a bar of unmagnetised steel or iron, each molecule may be a magnet, but the molecules are grouped into numerous independent magnetic chains. These chains become broken up by the process of magnetisation, which causes all the molecular magnets to turn into line. This is known as **Weber's Theory of Magnetisation**, our knowledge of which has been greatly advanced by the work of Professor J. A. Ewing.

The question is still unanswered as to how and why the molecules of steel or iron are natural magnets, and it can scarcely be discussed in this small book. It must suffice to apply the theory to the simpler magnetic phenomena, and to obtain thereby an explanation of the experimental results observed.

Application of Theory. (i.) *The process of magnetisation.*—With slight magnetisation the molecules merely turn through a slight angle, giving a slight excess of north-seeking polarity in the direction of the magnetising force, and slight excess of south-seeking polarity in the opposite direction. As the magnetisation proceeds, the molecules turn gradually more into line.

EXPT. 52.—Place a group of several compass-needles close together on the table. Observe the relative directions

in which the needles point. Gradually bring one pole of a bar-magnet near to the group, and observe how the needles are slowly deflected into line. When once in line the needles are not affected by bringing the bar-

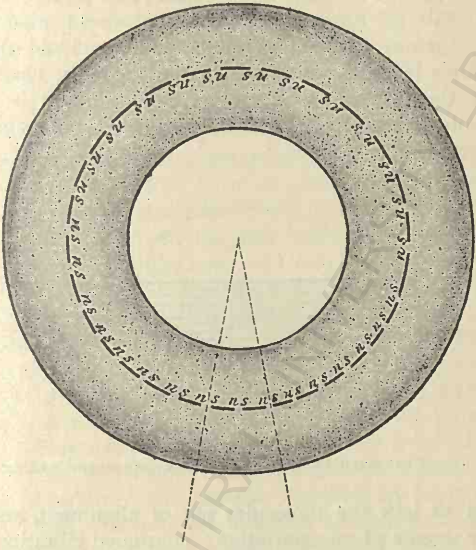


FIG. 64.—An iron ring magnetised axially.

magnet still nearer to the group. When the magnet is removed to a distance, the needles, being free to move, immediately swing back till their directions are higgledy-piggledy once more.[1]

(ii.) *Saturation.*—When all the molecules point exactly in the direction of the force, an increase of the latter will not produce any further effect—in fact, the magnet is saturated.

This complete alignment[2] may be difficult to obtain in

[1] This can be well shown to large classes by using the horizontal projecting appliance of a lantern, and using compass-needles, the cases of which have glass top and bottom.

[2] The word *alignment* is intended to convey the idea that the molecular magnets are arranged in line and end-to-end.

practice; some of the chains of molecules near the sides of the magnet may be comparatively short, forming short open magnetic chains, the external magnetic forces due to which will give the characteristic polarity to the surface of the magnet where they emerge into the outer space (Fig. 65).

(iii.) *Effect of Vibration.*—Vibration would give to the molecules greater freedom to move, and would aid the magnetising force in breaking up the closed magnetic chains. At the same time, vibration of a bar-magnet which is already magnetically saturated would, in the absence of the magnetising

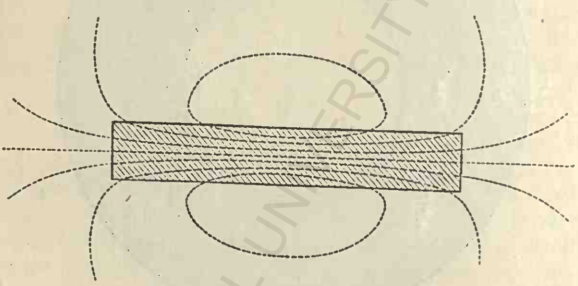


FIG. 65.—A bar-magnet may consist of many open magnetic chains.

force, tend to jerk the molecules out of alignment, and so to reduce the degree of magnetisation; continued vibration would tend to bring the molecules back into the condition of closed magnetic chains.

(iv.) *Retentivity.*—In the absence of vibration, the maintenance of perfect alignment would depend upon the forces which might resist any tendency to rearrangement. Such forces might be caused by *mechanical friction* or by the *mutual magnetic forces*, and they are well marked in the case of steel, but almost absent in soft iron. Expt. 52 is analogous to the behaviour of soft iron, and the same experiment would in some features resemble the behaviour of steel if the needles were swinging in thick treacle instead of in air.

(v.) *Susceptibility.*—Just as the forces resisting any return to the closed chains is greater in steel than in soft iron, so also are the forces resisting the breaking-up of the magnetic

chains greater in steel. The same magnetising force will cause a greater disturbance in the soft-iron molecules than in the steel molecules.

(vi.) *Elongation of a bar when magnetised.*—The deflection of the molecules into line when a bar is magnetised would probably cause a slight change in the dimensions of the bar. Joule found that when a bar of steel is strongly magnetised, it actually does elongate to the extent of $\frac{1}{720{,}000}$ of its length.

(vii.) *Magnetic Induction.*—This is considered fully in the next section.

Behaviour of Soft Iron in a Magnetic Field.—If a bar of soft iron is placed in a magnetic field, with its length coinciding with the direction of the magnetic lines of force, the molecular magnets of the soft iron will be pulled partially or completely into alignment, according to the magnitude of the magnetising force. The molecular north-seeking poles will tend to point in the positive direction of the force, and the south-seeking poles in the opposite direction. The ends of the iron will possess polarity, and the lines of force traversing its length will be partly those of the magnetic field in which the soft iron is placed, and partly those originating from its own molecular magnets. The latter lines were originally hidden owing to the molecules being grouped in closed magnetic chains. The iron has become temporarily *magnetised by induction*, and evidently the essential condition for this is that the lines of force shall pass along the length of the iron. *At all points where lines of force enter the iron we find a region of south-seeking polarity, and a region of north-seeking polarity where they emerge.* If the iron is so situated that the lines of force pass through the iron from side to side perpendicularly to its axis, then no lines of force traverse its length and no polarity is found at the ends; in such a case the polarity will be found distributed along the two sides.

Hence, in order to magnetise a bar of soft iron by induction, so as to create polarity at the two ends, it is necessary to place the iron in the field so that the lines of force pass through the iron in the direction of its axis.

The same effects will be obtained with steel, but to a much smaller degree, since its *susceptibility* is less.

Expt. 53.—Take a map of the field of force due to a bar-magnet, near to which is placed a bar of soft iron, as shown in Fig. 66.

An iron-filing map will indicate how the lines of force curve in toward s^1, and how they spread out again after leaving n; and the map will also suggest that there are fewer lines of force in the external space on either side of the soft iron; in other words, the *intensity* of the field at these points is diminished. The change in the intensity of the field at any point might be observed by determining the rate of swing of a compass-needle (or heavy suspended magnetic needle) when the soft iron is present, and when it is removed. It would be found that the intensity at the points A, B, and C is diminished, but that it is increased at D. These results would be anticipated by considering the forces of attraction and repulsion which would act upon a single north-seeking pole when placed at the point in question. Thus, at A, the forces due to N and S will be partially neutralised by the forces due to s and n,[1] the resultant force will be diminished, and hence *the intensity of the field at A is less.* The same method of reasoning will determine the changes of intensity at the other points.

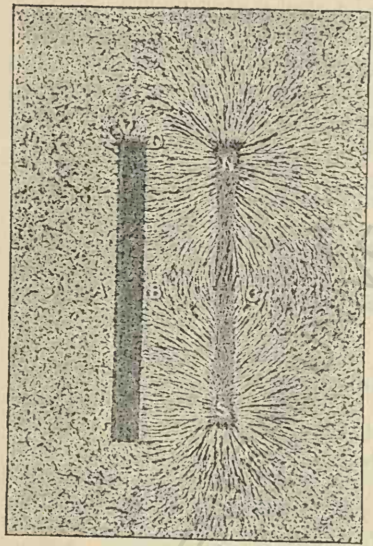


Fig. 66.—A bar of soft iron placed near to a bar-magnet.

The appearance of the map suggests that the lines of force prefer to travel through the iron rather than the surrounding

[1] The letters n, s, refer to the polarities induced in the soft iron bar.

air. This idea is sometimes expressed by saying that *iron, or any other magnetic substance, conducts lines of force better than air.* The effect of iron in a magnetic field is to some extent analogous to an open gap in a hedge, across which a strong wind is blowing; more air passes through the gap than through an equal length of the hedge, since the gap offers less resistance to the passage of the air; the *stream-lines* (or lines indicating the direction of flow) of the air converge towards the gap, and diverge again on the opposite side of the hedge. The gap may be regarded as a better conductor for air than the hedge. In a magnetic field the lines (which do not indicate directions of *flow* but rather *directions of force*) converge towards the iron in a similar manner, and the degree to which this takes place depends upon the softness of the iron.

Permeability.—The effect of soft iron in a magnetic field is more accurately expressed by saying that *magnetic substances have greater magnetic permeability.*

Permeability may be defined as the property, possessed in varying degree by magnetic substances, of becoming magnetised when placed in a magnetic field. If a piece of soft iron is placed within a magnetic field, the number of lines of force, including those due to the original field and those due to the iron, within the iron and traversing each square cm., drawn perpendicularly to the direction of the field, is termed the *magnetic induction*, and is denoted usually by the symbol B. If H represents the initial intensity of the field, then the *permeability* is expressed numerically by the ratio B/H.

Of the few magnetic substances which are known, soft iron has by far the highest permeability. All substances other than those which are magnetic have the same permeability as air.

Magnetic Screens.—*When soft iron is placed in a magnetic field, and causes the intensity of the field to be diminished at any neighbouring point, it is said to magnetically screen that point.*

If a thick piece of soft iron is placed near to the pole of a bar-magnet as shown in Fig. 67, many of the lines of force appear to traverse the iron from its centre towards either end; only a few lines appear to pass beyond the distant side of the iron screen. The centre of the iron screen will have south-

seeking polarity, and both ends will have north-seeking polarity. The deflection of a compass-needle at A will be diminished by interposing the slab of soft iron.

This is not the only position of the iron slab which will

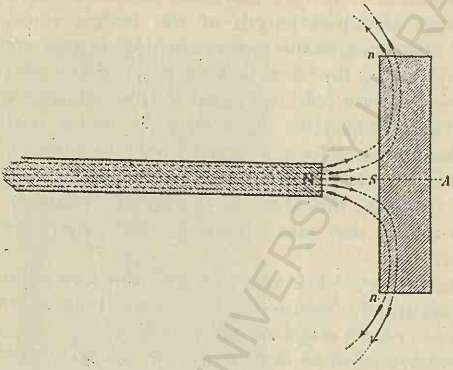


FIG. 67.—The point A is magnetically screened by a slab of soft iron.

screen the needle; in fact, the point A will be more fully screened if the slab is placed in other positions. Assuming

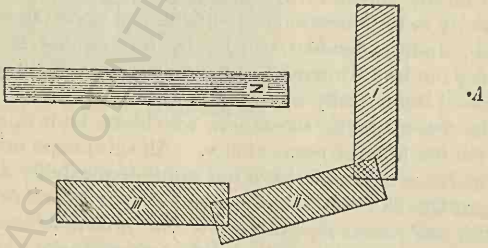


FIG. 68.—A slab of soft iron at iii. will screen A more completely than if placed at i.

that all the lines of force emerging from N return by more or less circuitous routes to the opposite pole of the magnet, the slab of iron will have a greater effect if it is placed in such a position as to offer as direct a path as possible to the lines of

force returning to the opposite pole of the magnet. According to this reasoning, the screening effect in position ii. (Fig. 68) will be greater than when placed in position i. The effect will be still more marked if the slab is placed in position iii.

By considering the polarity induced in the soft iron under such conditions, it is easy to explain (by the Primary Law of Magnetic Attraction and Repulsion) *why* the screening takes place, since in each position the induced south-seeking polarity in the soft iron will tend to neutralise the forces due to the north-seeking polarity of the magnet.

EXPT. 54.—Support a bar-magnet on a wooden block about 20 cms. to the east or west of the magnetometer needle. Note the deflection. Interpose a slab of soft iron (2 cms. thick) and note the change of deflection. Place the slab in various positions and note the deflection in each case. Observe what position of the slab affords a maximum screening of the needle. If a thick slab of soft iron is not available, the screening effect can be satisfactorily shown by using two or three thicknesses of galvanised iron-sheet.

The screening may also be detected by comparing the rate at which a suspended magnetised needle swings to and fro at the point which is under examination.

The most perfect form of magnetic screen is obtained in the case of a hollow sphere of thick soft iron. The space within the sphere may be said to be absolutely free from lines of force, all of which will pass through the substance of the iron shell (Fig. 69). The diagram indicates the general distribution of the lines of force in a section through the centre of the sphere. This principle has been applied by Lord Kelvin to the screening of ship galvanometers from magnetic disturbances by placing the galvanometer inside a hemispherical shell of soft iron.

Theory of Magnetic Keepers.—It may be assumed that a bar-magnet consists of a large number of open magnetic chains of molecular magnets, and that the degree of magnetisation depends upon the completeness of alignment of the molecular magnets. Any subsequent treatment which tends to break up the magnetic chains will diminish the degree of magnetisation. A magnetic chain is more readily disturbed

at its ends than at its centre, since a molecular magnet near to the centre is held in position by the mutual magnetic forces of the neighbouring molecules in the same chain, while the molecular magnets at the extreme ends of the chain have a restraining magnetic force acting on one pole only. The latter are consequently more sensitive to vibration or physical disturbance. In order to preserve the strength of

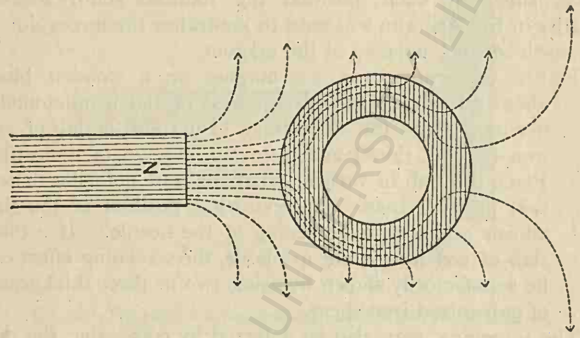


FIG. 69.—The screening effect of an iron shell.

a magnet, it is necessary to lengthen the magnetic chains artificially so that the end molecules may be kept in position just as completely as those near to the centre. This explains the purpose of magnetic keepers. In the case of a horse-shoe magnet, the keeper is magnetised so long as it is in contact with the poles, and its polarity is such that it tends to keep the end molecules in position. The open magnetic chains of the magnet now become closed chains, which are situated partly in the magnet and partly in the keeper. The same result is obtained by placing two bar-magnets side by side with unlike poles together, and the ends connected by soft iron keepers.

Nearly all the lines of force passing between the poles of the horse-shoe will pass through the iron keeper instead of taking a more circuitous route through air; the space beyond the keeper will consequently be screened from the magnetic forces due to the magnet (Fig. 70).

Pen-and-Ink Diagrams of Magnetic Fields.—In a subject which is so essentially experimental it is important that

the student should pay special attention to the rapid drawing of explanatory diagrams. A simple sketch is often more useful than a page of manuscript. Before making a sketch the following points should be considered:—

(i.) Decide from what point of view the diagram should be drawn. A choice must be made between a vertical cross-section, a bird's-eye view, and a perspective view. The last method is the most difficult to adopt successfully, and is seldom required.

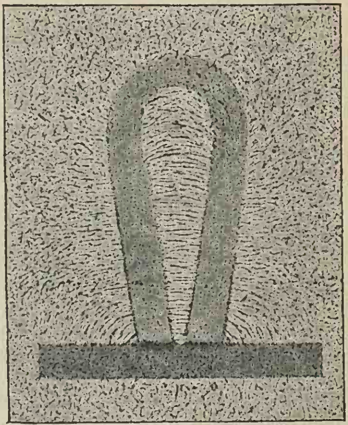


FIG. 70.—A soft iron keeper converts a horseshoe magnet into a closed magnetic chain.

(ii.) All fundamental magnetic phenomena depend upon the *directions* and the *magnitudes* of the forces which are called into play. The student is now thoroughly conversant with the fact that *the lines of force* trace out the directions of the forces, and it is well to add that a simple diagram is also capable of suggesting the magnitudes of the forces. It is generally accepted that a region of greater magnetic force shall be represented diagrammatically by an increased number of lines of force. If a field of small intensity is represented by one line of force passing through a cross-section of the field 1 sq. cm. in area, then a field of double that intensity is represented by two lines of force passing each sq. cm. of cross-section. On this principle a student can readily represent in a sketch the distinction between regions of small intensity and of great intensity.

(iii.) Do not attempt to sketch too many lines of force; three or four will often be sufficient. Carefully select those lines only which affect the experimental results, and draw them with as much accuracy as possible. Remember that each line of force is a complete loop, and should be represented as such; do not allow the line to appear to have two free ends connecting

regions of opposite polarity, but complete the course of the line through the magnet, or soft iron, as the case may be.

(iv.) Represent by means of arrow-heads the directions of the lines of force.

Chief Points of Chapter VII

Each Magnetic Line of Force is a complete loop, and does not possess two free ends. The lines of force proceeding from the north-seeking pole of a magnet re-enter the magnet at its south-seeking end, and traverse the length of the magnet to their origin.

Each Molecule of a Magnet is a complete magnet in itself.

Weber's Theory.—Each molecule in an unmagnetised bar of iron or steel may be a magnet, but the molecules are grouped into numerous independent magnetic chains. The process of magnetisation consists in breaking up these chains, and turning into line the molecular magnets, with like poles pointing in the same direction.

A closed magnetic chain consists of a group of magnets so arranged that the magnetic forces due to any member of the group are neutralised by the forces due to the other members of the group. The best example of a closed magnetic chain is an iron ring which is magnetised along the curved axis of the iron.

An open magnetic chain is an incomplete closed magnetic chain, thus affording a resultant external magnetic field.

Application of Weber's Theory. (i.) *Saturation.*—A bar-magnet is magnetically saturated when all its molecules are in complete alignment.

(ii.) *Effect of Vibration.*—Vibration will aid the magnetising force to break up the closed magnetic chains. If the magnetising force is removed, vibration will tend to jerk the molecules out of alignment, and so reduce the degree of magnetisation.

(iii.) *Retentivity* is attributed to internal forces (dependent upon either mechanical friction or mutual magnetic forces). Such forces are well marked in steel, but almost absent in soft iron.

(iv.) *Susceptibility.*—The same internal forces as those to which Retentivity is attributed would also explain the characteristic difference in Susceptibility between soft iron and steel.

(v.) *Elongation of a bar when magnetised* may be attributed to the molecules of iron or steel being drawn into alignment.

Behaviour of Soft Iron in a Magnetic Field.—When magnetic lines of force traverse a piece of soft iron its molecular magnets will be partially or completely pulled into alignment. The final number of lines of force traversing the iron will be partly those of the field in which the iron is placed, and partly those originating from its own

molecular magnets. At points where lines of force enter the iron we find a region of south-seeking polarity, and a region of north-seeking polarity where they emerge.

A map of a magnetic field in which a piece of soft iron is placed suggests that the lines of force prefer to travel through iron rather than air; in other words, that soft iron *conducts* the lines of force better than air.

Permeability is the property, which a magnetic substance possesses, of becoming magnetised when placed in a magnetic field.

$$\textit{Permeability} = \frac{\text{Intensity of magnetisation inside the iron}}{\text{Intensity of the magnetising field}}.$$

Soft iron has a far higher Permeability than steel.

Magnetic Screens.—When soft iron is placed in a magnetic field, and causes the intensity of the field to be diminished at any neighbouring point, it is said to magnetically screen that point.

Theory of Magnetic Keepers.—A closed magnetic chain is far more stable than an open chain. An ordinary permanent magnet consists of a large number of open chains which become closed chains when the keeper is attached to the magnet-poles. A keeper magnetically screens the surrounding space near to the poles of a magnet.

Questions on Chapter VII

1. Describe an experiment by which you would prove that lines of force are present inside a magnet.

2. A thin steel magnet is broken into several pieces. Explain, with the aid of a diagram, the polarity which would be found at the ends of each piece.

3. Explain what is meant by the terms *open magnetic chain* and *closed magnetic chain*. Give a diagram of an example of each.

4. Give a brief description of Weber's Theory of Magnetisation. State how the theory affords an explanation of the phenomenon of magnetic saturation.

5. Describe an experiment by which you would show that magnetism is a property of the molecules of a magnet.

6. Joule has observed that a bar of steel elongates slightly during the process of magnetisation. What theoretical reasoning would lead you to anticipate this result?

7. Explain the meaning of the terms *Susceptibility* and *Retentivity*, and state the differences between soft iron and hard steel with regard to these characteristics.

8. A short piece of soft iron is to be magnetised inductively. State how it should be placed relatively to (i.) a bar-magnet, (ii.) a horseshoe magnet, in order to obtain a satisfactory result. Give diagrams.

9. Give a diagram of the lines of force due to a horse-shoe magnet (i.) with the keeper on, (ii.) with the keeper off. (Lond. Matric. 1897.)

10. Describe the difference between the magnetic properties of soft iron and hard steel. Which would you use (i.) for the core of an electro-magnet, (ii.) for a permanent magnet? Give reasons for your answer. (Lond. Matric. 1897.)

11. A glass tube is nearly filled with steel filings and corked at both ends. It can then be magnetised by any of the ordinary methods, but loses its magnetic properties when shaken. Explain this. (1894.)

12. A piece of soft iron and a piece of hard steel of the same size and shape are separately rubbed from end to end by the north pole of a strong bar-magnet. How will you test their magnetic condition, and what difference will you find between them? (1898.)

13. A piece of cardboard is placed over a horse-shoe magnet lying on a table, and iron filings are scattered over it. Draw a picture showing the arrangement assumed by the filings when the cardboard is tapped. If the poles of the magnet are joined by an iron keeper, how will the arrangement of the filings be modified when the cardboard is again tapped? (1894.)

14. Iron filings are scattered on a piece of cardboard which is placed over a horse-shoe magnet and tapped. What differences would be observed in the arrangement of the filings when the ends of the magnet were joined in turn by bars of (1) steel, (2) soft iron, and (3) copper? (1896.)

15. If you were required to magnetise a circular ring of steel so that it should show no sign of magnetisation, how would you proceed? and how, being allowed to deal with the steel in any way that you pleased, would you prove that it was really magnetised? (1897.)

16. An iron ball is held over a pole of a horse-shoe magnet. Will the attraction exerted on the ball be altered if the poles of the magnet are connected by a soft iron keeper, and, if so, in what way, and why? (1889.)

17. A long magnet and a piece of soft iron of the same size and shape are placed parallel to each other underneath a sheet of paper on which iron filings are strewed. How will the filings arrange themselves? (1891.)

18. A compass-needle is deflected by a bar-magnet placed some distance away from it. How is the deflection modified (if at all) when a bar of soft iron is placed parallel to, but not touching, the magnet? Give reasons for your answer. (1895.)

19. A compass-needle is deflected 15° from the meridian, when a bar-magnet is placed on the table some distance away. Will the deflection be altered if the poles of the magnet are connected by a bent iron rod? Give reasons. (1890.)

CHAPTER VIII

THE RELATIVE MEASUREMENT OF MAGNETIC FORCES

Apparatus required.—Long bar-magnet. Swinging magnet (Fig. 71). Squared paper. Short wire-nails.

The relative magnitudes of the forces at different points in the field of a bar-magnet may be deduced by the graphical method explained in Fig. 43, where the magnitudes of the forces are represented by the relative lengths of the lines representing the resultant forces nr; in fact, nr may represent the *intensity* of the field at n. Each pole of a compass-needle placed at n will experience a force which is proportional to nr, and also to the degree of magnetisation of the compass-needle.

Force acting on pole of compass-needle = Intensity of Field × Pole strength[1] of compass-needle;

or,
$$F = I \times m$$

(where F represents the force, I the intensity of the field, and m the pole strength of the compass-needle).

The rate at which a compass-needle swings to and fro depends upon the *magnitude* of the forces acting upon its poles; the greater the forces the more rapidly it swings. The rate of swing can accordingly be used as a method for comparing the magnetic forces at different points. This method was first devised by Coulomb in 1780.

The relationship between the force and the number of swings described by the needle in a given interval of time is

[1] A magnet-pole has unit strength when it repels an equal similar pole, placed 1 cm. distant, with a force of 1 dyne.

the same as that which holds good between the force of gravity and the rate of swing of a pendulum, *i.e. the force is directly proportional to the square of the number of swings.*

Comparing the forces at two points, the *ratio* between them will be numerically the same as the *ratio* of the squares of the number of swings described in equal intervals of time; or,

$$\frac{F_1}{F_2}=\frac{n_1^2}{n_2^2};$$

but

$$\frac{F_1}{F_2}=\frac{I_1\times m}{I_2\times m}=\frac{I_1}{I_2} \text{ (p. 97).}$$

Hence

$$\frac{I_1}{I_2}=\frac{n_1^2}{n_2^2}.$$

Experimental Determination of Relative Intensity.—In most cases the intensity of the field will be due to the combined intensities of a magnet's field, together with that of the earth. Assuming that the needle comes to rest pointing north and south, and that the forces due to the earth and the magnet act *in the same direction*, then the square of the number of swings is proportional to the *sum* of the forces. But if the forces act *in opposite directions*, the square of the number of swings is proportional to the *difference* of the forces. In the first case, if the needle makes n swings in a minute due to the earth alone, and n_1 swings in a minute due to the joint action of the magnet and the earth, then the force due to the magnet alone will be proportional to $(n_1^2-n^2)$. In the second case the force due to the magnet alone will be proportional to $(n_1^2+n^2)$.

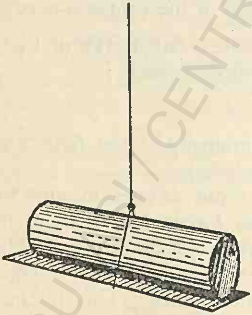


FIG. 71.—A weighted magnetic needle.

A useful application of this principle is the determination of the relative intensities of the magnetic field near to various parts of a long bar-magnet. The most convenient form of swinging-needle is a *very short* cylindrical steel magnet, and

sufficiently heavy to make the rate of swing comparatively slow, otherwise there will be difficulty in counting the swings accurately; or, instead of this, use a short piece of magnetised clock-spring, which is weighted by attaching it to a piece of zinc rod of the same length, or to a bundle of thick copper wires (Fig. 71).

EXPT. 55.—Support the needle by a length of thin copper tinsel. Clamp the bar-magnet vertically with its north-seeking pole uppermost, and so situated that it is exactly south of the position occupied by the needle (Fig. 72). Raise the needle until it is opposite the north-seeking pole of the magnet, and about 2 cms. distant. Remove the magnet to a distance, and count the number of swings described in a minute due to the earth alone. Replace the magnet in its original position, and again count the number of swings. Repeat this, with the needle opposite a point a little below the pole of the magnet, and at the same horizontal distance from the magnet; proceed in this manner until ten or twelve independent observations have been taken opposite different points of the magnet. In each observation measure the vertical distance from the centre of the magnet. Tabulate the results in the following manner:—

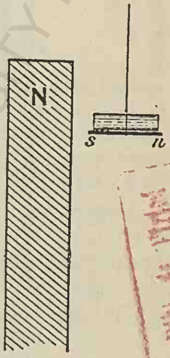


FIG. 72.—To illustrate Expt. 55.

Vertical Distance.	n_1.	n.	$(n_1^2-n^2)$.

Notice that, opposite the centre of the magnet, n_1 is

approximately equal to n; this shows that at this point the magnet exerts no force on the needle.

Exactly the same method may be used in order to compare the intensities at different parts of a magnetic field; for example, the method may be applied to the comparison of the intensity of the earth's magnetic field in different localities.

Diagram of Magnetic Intensities.—The changes in

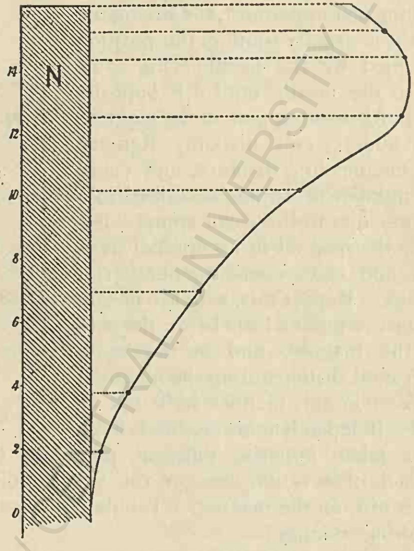


FIG. 73.—Diagram of the intensity of the field near to a bar-magnet.

the intensity of the field can be more clearly understood if the results of this experiment are plotted out on squared paper.

EXPT. 56.—Draw the outline of the magnet on the paper, its length coinciding with the vertical lines. Mark the points opposite which observations were taken, and measure horizontal distances from each point, the distance in each case being proportional to the numerical value of $(n_1^2 - n^2)$ for that point.

The curve joining the ends of these horizontal lines indicates

how the magnetic intensity falls off towards the centre (Fig. 73).

With care it is possible to observe that the regions of maximum intensity are situated a small distance *away* from the extreme ends of the magnet. This would be anticipated by referring to Fig. 41, where it is shown that the *resultant magnetic forces* due to an ordinary bar-magnet originate from points slightly distant from the ends.

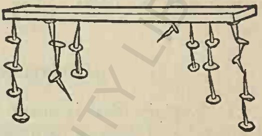


FIG. 74.—To illustrate Expt. 57.

The intensity of the field at any of the points adopted in the experiment is dependent upon the pole strength of that part of the magnet which is near to the point. The same diagram may therefore be regarded as *a map of the distribution of polarity on the magnet* itself. This may be experimentally determined by comparing the weight of soft iron which can be supported from the various parts of the bar-magnet.

EXPT. 57.—Clamp a long bar-magnet in a horizontal position, and magnetically attach short wire-nails at intervals along the length of the bar-magnet; attach other nails to these, and continue adding to the length of each chain until no more can be supported (Fig. 74).

A line connecting the ends of the chains will closely resemble the curve obtained in the previous experiment.

CHIEF POINTS OF CHAPTER VIII

The Intensity of a Magnetic Field is measured by the force it exerts on a magnet-pole of unit strength.

Force acting on a magnet pole = Intensity of Field × Pole strength of magnet.

The Rate of Swing of a suspended magnet depends upon the magnitude of the forces acting on its poles.

(Rate of swing)^2 is proportional to the Force.

If two different fields are to be compared, and F_1 and F_2 are the forces which they respectively exert on a magnet-pole, then

$$\frac{F_1}{F_2}=\frac{n_1^2}{n_2^2};$$

but
$$\frac{F_1}{F_2}=\frac{I_1\times m}{I_2\times m}=\frac{I_1}{I_2}.$$

Hence
$$\frac{I_1}{I_2}=\frac{n_1^2}{n_2^2},$$

or the ratio of the intensities of two fields is equal to the ratio of the squares of the number of swings of a magnet in a given time when swinging in the fields.

Questions on Chapter VIII

1. Explain what is meant by the term *Intensity* of a magnetic field. Explain also how a pen-and-ink diagram representing a map of a magnetic field may be made to suggest differences of intensity at different points.

2. In what manner does the rate of swing of a magnet depend upon the intensity of the field in which it is placed?

3. A vertical steel rod, of which a portion, the length of which is less than half the length of the rod, is stuck into the earth, is found to be rather strongly magnetised. If you were given a compass and a foot-rule, how could you, without disturbing the rod, form an estimate of the length of the buried portion?

4. A compass-needle makes 10 oscillations in half a minute due to the earth alone. The earth and a magnet **A** cause it to make 12 oscillations in half a minute. When **A** is replaced by a magnet **B** the needle makes 14 oscillations in the same time. What are the relative intensities of the magnets **A** and **B**?

5. A long bar-magnet lies north and south magnetic, with its north-seeking end towards the south. A compass-needle is situated on the magnetic axis of the bar produced. What is the effect on the rate of vibration of the needle of sliding the bar nearer to the needle?

6. A suspended bar-magnet is made to vibrate at three different stations, **A**, **B**, and **C**. At **A** it makes 20 vibrations in one minute; at **B**, 18 vibrations in forty-five seconds; at **C**, 25 vibrations in one minute. Find numbers proportional to the intensity of the fields at the three stations.

7. A bar-magnet is placed with its centre due east of a compass-needle, and with its axis parallel to the magnetic meridian. How will you determine whether the intensity of the magnetic field at the needle is increased or diminished? Farther, how will you compare the field with that which existed there before the bar-magnet was brought near? (1896.)

CHAPTER IX

TERRESTRIAL MAGNETISM

Apparatus required.—Bar-magnet. Compass-needle. Several knitting- and sewing-needles. Strip of galvanised iron (30 cms. × 2 cms.). Silk thread. Flat cork. Models of dip-needle and astatic pair. Magnetometer.

The Earth a Magnet.—The characteristic manner in which a compass-needle swings to and fro and finally comes to rest pointing approximately north and south, even in the absence of any neighbouring magnet, suggests that the earth itself must be enveloped in a field of magnetic force. If this is so, then a piece of soft iron will become temporarily magnetised if held with its axis pointing in the same direction as that in which a compass-needle will point.

EXPT. 58.—Hold a strip of thin galvanised iron (about 30 cms. × 2 cms.) so that it is pointing approximately north and south. Tap it gently with the knuckles. Test its polarity by bringing its ends near to a compass-needle. The end pointing towards the north has acquired north-seeking polarity. Now hold the iron with its north-seeking pole pointing towards the south, and again tap it. Notice that its polarity is now reversed. Finally, hold the iron in an east and west position and again tap it. Notice that all polarity has disappeared.

The tapping may even be dispensed with if the soft iron is simply kept in position and the compass-needle is brought near to its ends in order to detect the polarity.

Evidently there are lines of magnetic force originating from a region of north-seeking polarity in the neighbourhood of the south geographical pole, and traversing the earth's surface

towards a region of south-seeking polarity in the neighbourhood of the north geographical pole.

In the year 1269 Peter Peregrinus (or Peter the Pilgrim) wrote a letter on the construction of the magnetic compass, and described how *the lodestone stands in the direction of the north pole of the heavens.* This opinion, that the directive power of the compass-needle was due to the pole-star, was held until the time of Dr. Gilbert, who discovered that the earth itself was a great magnet, and that the forces acting on a compass-needle originated from the earth. Gilbert also found, by testing with a compass-needle, that all iron pillars and railings were magnetised.

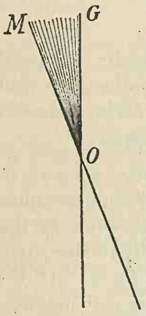


FIG. 75.—The angle MOG is the declination at O.

Declination.—*The* geographical meridian *at any point of the earth's surface is the vertical plane passing through that point and through the poles of the earth. The* magnetic meridian *at any point is the vertical plane passing through the axis of a compass-needle placed at that point.* In most localities on the earth's surface these two meridians do not exactly coincide. **The angle** *between the magnetic meridian and the geographical meridian at any point is called the* **Declination** *at that point.* In Fig. 75, the line **OG** represents the geographical meridian, and **OM** the magnetic meridian, at the point **O**. The angle **MOG** is the **Declination at O**.

The fact that the compass-needle does not point to the true north was first observed by Columbus when on a voyage in 1492. He found that, at a point near to the Azores, the compass pointed true north, but that in regions to the east of this it pointed west, and that in regions to the west it pointed east of true north.

It is impossible to determine the declination by a lecture-room experiment, since the geographical meridian, or a *true* north and south direction, can only be found by observations of the sun, north star, or other heavenly bodies. A simple way to determine true north and south by observations of the sun is as follows:—

EXPT. 59.—Fix a rod upright in a place where the sun can shine upon it. About an hour or two before mid-day observe the direction and length of the shadow of the rod, and by means of a piece of string fitting loosely upon the rod mark out a circle having a radius equal to the length of the shadow. In the afternoon, when the shadow has the same length as in the morning observation, mark its direction. A line bisecting the angle between the directions of the morning and afternoon shadows is a true north and south line (Fig. 76).

In this country, and in many other localities, the compass-needle points to the *west* of true north. Elsewhere the Declination is easterly, while there are comparatively few localities where the needle points due north. The Declination at Greenwich was 16° 5′ W. in 1904, and diminishes at the approximate rate of 6′ per annum.

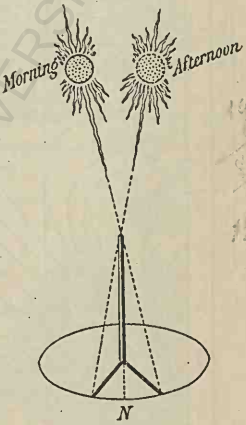


FIG. 76.—Method of determining the geographical meridian.

The magnitude of the Declination in any locality is not constant, but changes slowly from year to year. This *secular change*, as it is termed, was first observed in 1580 by Burroughs (comptroller in the navy in the time of Queen Elizabeth). In that year the Declination in London was 11° E.; this gradually diminished, and in 1657 the needle pointed due north. The Declination then became *westerly*, and reached a maximum value of 24° 30′ W. in 1816. Since that date it has been slowly diminishing to its present value. It is estimated that 320 years are required for a complete cycle in the changes of the Declination.

In addition to the secular change there is a very slight cycle of changes observed day by day, which is termed the *Diurnal change*.

It will be readily understood how important it is that the

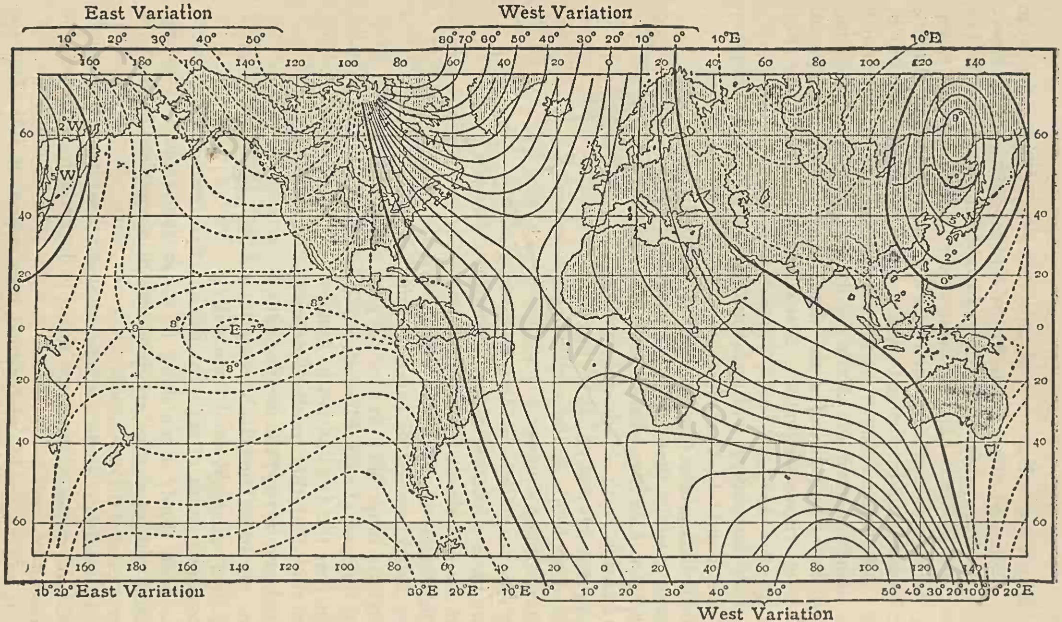


FIG. 77.—Isogonic lines, or lines of equal declination. (For the year 1905.)

Declination should be known at all points of the earth's surface, and more especially for purposes of navigation. Magnetic maps are drawn up in which the Declination is marked for as many localities as possible, and the utility of the map is considerably increased if lines are drawn connecting localities which have the same Declination. Such a line is termed an **Isogonic Line.** Lines connecting localities of *no* Declination are termed **Agonic Lines.** Fig. 77 represents a map of the world on which these lines have been drawn. It will be noticed that there are two *agonic lines;* one passes through Hudson's Bay, the Gulf of Mexico, and Brazil; another passes through St. Petersburg, Persia, the Indian Ocean, and Western Australia. Between these two lines is an extensive area where the Declination is *westerly.* A third agonic line forms an oval in Siberia, China, and Japan; within this oval the Declination is also *westerly.* In all other localities the Declination is *easterly.*

Magnetic Dip.—Are the lines of force due to the earth horizontal? It does not follow that, because a compass-needle supported on a pivot remains horizontal, the lines of force acting upon it are also horizontal. Even if the lines of force are inclined to the horizontal, it may still be possible for them to have a directive action on the needle. In Fig. 78 let ns represent a compass-needle, and nI, sI' the forces due to the earth's field. The force nI may be regarded as the resultant of two separate forces—nH the *horizontal component*, and nV the *vertical component*. Similarly, sI' may be regarded as the resultant of the two forces sH' and sV'. The forces nH and sH' will pull the needle into the magnetic meridian, while nV and sV' will simply tend to tilt the needle out of the horizontal. The weight of the needle is usually sufficient to mask the

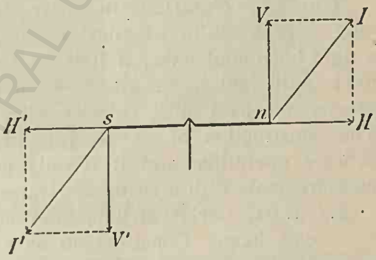


FIG. 78.—A compass-needle acted upon by magnetic forces inclined to the horizontal.

effects of the latter forces. It will be found that the earth's lines of force actually are inclined to the horizontal in most localities, and the tendency to tilt the needle is neutralised by making it slightly heavier at one end.[1]

EXPT. 60.—Suspend a long knitting-needle by *tying* a silk thread to it, and adjust the thread so that the needle swings horizontally. Carefully magnetise the needle without disturbing the position of the thread. Observe that the needle now dips down with its north-seeking pole downwards. Since the needle naturally tends to take up a position *along the lines of force*, it follows that the latter must be inclined to the horizontal.

This phenomenon was first announced by Robert Norman in his book *The New Attractive* (published in 1576); he proceeded to construct a needle which would move freely in a *vertical* plane round a horizontal axle, and called it a *Dipping Needle.*

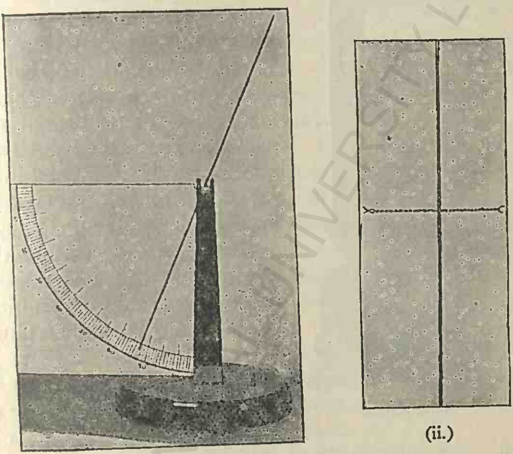
The angle between the axis of a magnetised needle, which is free to move in the vertical plane of the meridian, and the horizontal line through its point of support is called the Dip.

The Dip-Needle.—In order that a magnetised needle may move freely in a vertical plane, it must be supported on a rigid horizontal axle; if it is to be influenced by magnetic forces only, and to be absolutely independent of the force of gravity, the axle must coincide with the centre of the needle. The construction of an accurate dip-needle is an extremely delicate operation, and it is only possible to obtain correct measurements with a costly apparatus.

EXPT. 61.—Select an unmagnetised knitting-needle about 12 cms. long. Construct an axle for the needle in the following manner:—Hold two short pieces of copper wire on opposite sides of and at right angles to the length of the needle. Twist the ends of the wires together on each side so as to grip the needle tightly, and carefully straighten the twists. Make the wire surfaces as smooth as possible by heating in a gas-flame and applying sealing-wax, shaking off the excess of wax while still fluid

[1] The student will now readily understand that the map of the earth's field obtained in Chap. VI. (Expt. 40) is really a map of the *horizontal* components of the earth's magnetic field.

(Fig. 79, ii.). Apply a spot of sealing-wax so as to rigidly connect the axle to the needle. Make a support for the needle by cutting two rectangular pieces of sheet brass or copper (7 cms. × 1 cm.), rigidly connect them together at the base with their short edges horizontal and 1 cm. apart, and fix them to a suitable base-board (or a support may be made with two pieces of glass-rod fixed horizontally and 1 cm. apart). Attach a circular scale of 90° to



(i.) (ii.)

FIG. 79.—A simple form of dip-needle.

one of the supports (Fig. 79, i.). See whether the needle is truly balanced by supporting it by its axle on the knife-edges; if necessary, adjust the position of the axle by slightly warming the sealing-wax joint and moving the axle along the needle. Carefully magnetise the needle. Place it on the knife-edges with its axle coinciding with the centre of the circular scale. Determine the magnetic meridian by means of a compass-needle, and mark the direction of this on the table. Place the needle so that it swings freely in the vertical plane of

the meridian. Observe the angle of dip. Make the needle swing slightly and again observe the dip. Repeat several times.

It will be observed that the axle is horizontal and perpendicular to the meridian, and that both the *horizontal* and *vertical components* of the earth's field (see Fig. 78) influence the position of rest. If the axle is horizontal and parallel to the meridian, only nV and nV′ (Fig. 78) will determine the position of rest (while nH and nH′ will simply tend to bend the axle), hence, with the axle in this position, the needle will come to rest pointing vertically downwards. This principle is applied in more elaborate forms of dip-needle in order to determine the magnetic meridian (instead of using a compass-needle). The stand of the needle, supported over a horizontal circular scale, is rotated until the needle is vertical, and is then turned through 90° so as to bring the axle *perpendicular* to the meridian. The angle of dip is then observed. An instrument of this character is represented in Fig. 80.

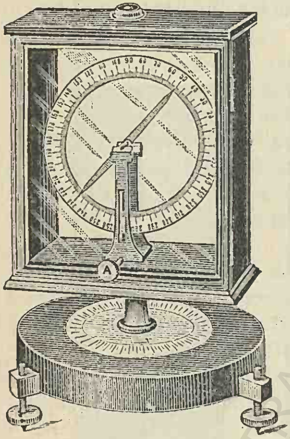


Fig. 80.—A dip-needle.

Angle of Magnetic Dip in various localities.—The Dip, like the Declination, differs in different localities, and also changes from year to year. The Dip in London, for the year 1898, was 67° 11′, and is 66° 57′ in the year 1904. Near to the equator localities are found where the Dip is *nil.* As the needle is conveyed northwards the Dip gradually increases, and at a point in Boothia Felix (North America) Sir John Ross found, in the year 1831, that the dip-needle was exactly vertical. This region must be one of south-seeking polarity; it is one of the so-called *magnetic poles* of the earth. As the needle is conveyed southwards from the equator, the south-seeking pole of the needle dips downwards, and the amount of

dip gradually increases as the south pole of the earth is approached. (The exact locality in the southern hemisphere in which the dip-needle sets vertically has not yet been determined.)

The *secular change* in the Dip is far less in magnitude than that of the Declination. Thus, in the year 1576 it was 71° 50′ at London, in 1720 it was 74° 40′, and at the present time it is diminishing at about the rate of 2′ of arc every year.

The magnitude of the Dip has been determined in many localities, and a map is reproduced, in Fig. 81, in which points of equal Dip are joined together by continuous lines which are called **Isoclinic Lines**. The line of *no Dip* is termed the *magnetic equator*, and it will be observed that it by no means coincides with the geographical equator.

The Directive Action of the Earth's Field.—

EXPT. 62.—(i.) Fix a magnetised sewing-needle to a flat cork with wax so that the needle is horizontal when the cork is floating on water contained in a dish. Float the cork on the water so that the needle points east and west. Notice how the needle rotates into the magnetic meridian, *but does not tend to move bodily towards the side of the dish.*

(ii.) Hold the pole of a bar-magnet near to the needle. Notice how the needle not only points in a definite direction depending upon the position of the magnet, *but also moves bodily towards the magnet.*

We say that the action of the earth's field is only *directive*, and not *translatory* also. The difference observed in the above experiments may be readily explained by applying the Law of Inverse Squares. The forces due to either of the earth's magnetic poles acting on the two poles of the needle are opposite in direction. The distance of the earth's magnetic pole from this latitude is several thousand miles, in comparison with which the length of the needle is quite infinitesimal. Hence the two poles of the needle may be regarded as being *equally distant* from the earth's magnetic poles, and the forces acting on the needle will therefore be equal in magnitude—in fact, the forces will act like a mechanical couple (see Fig. 30), drawing the needle into the meridian, but not tending to move it bodily in either direction.

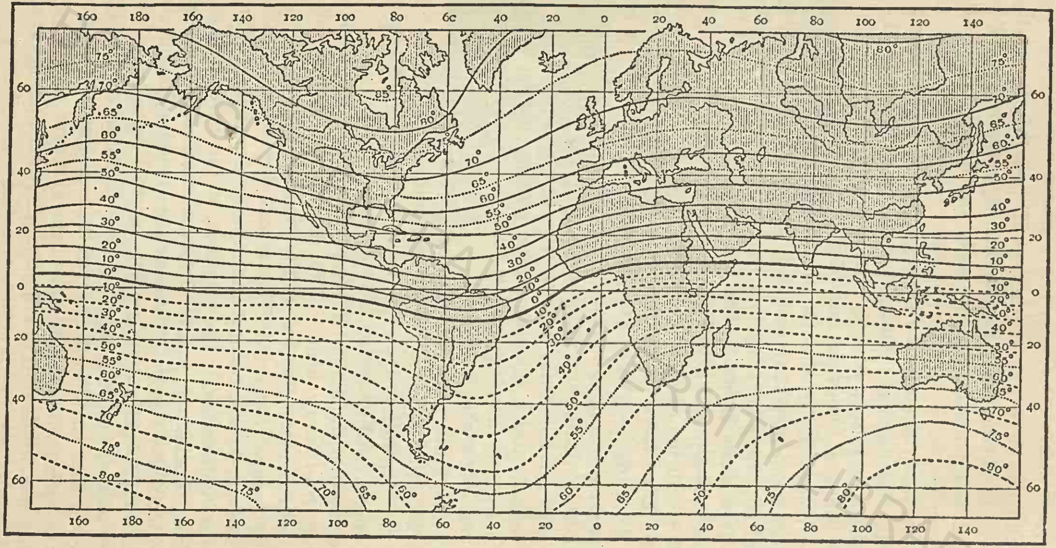


FIG. 81.—Isoclinic lines, or lines of equal dip. (For the year 1905.)

When the pole of a bar-magnet is held near to the needle the length of the needle is no longer small compared with the distance away of the magnet-pole. One pole of the needle will be considerably nearer to the magnet-pole than the other, one force will be greater than the other, and the floating needle will bodily move in the direction of the greater force.

The more distant pole of the magnet will exert forces opposite in direction to those due to the nearer pole, and will therefore tend to diminish the translatory effect seen in Expt. 62 (ii.). The translatory effect is therefore more marked if a *long* bar-magnet is used rather than a short one. If a very long bar-magnet is used the neutralising effect of the distant pole becomes quite negligible.

Behaviour of Soft Iron in the Earth's Magnetic Field.—A piece of soft iron is subject to magnetic induction when placed in *any* magnetic field, whether due to the earth or to an artificial magnet. If the field is due to the earth, the degree of magnetisation obtained is comparatively feeble, because the intensity of the earth's field is small compared with that which is found near to an ordinary bar-magnet. But the character of the changes produced in the field by the iron is of exactly the same nature in both cases. The lines of force will appear to be drawn into the iron, and will create polarity at the points of entrance and exit. A map of the earth's field in the neighbourhood of a piece of soft iron cannot be successfully obtained by the iron-filing method owing to the forces being so weak, but the compass-needle method will afford an instructive map.

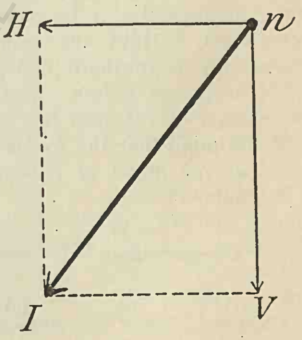


FIG. 82.—Horizontal and vertical components of a magnetic force.

Determination of Dip by Induction in Soft Iron.—When a piece of soft iron is held in the earth's field, the maximum degree of magnetisation is obtained when the iron is held so that its axis points *along* the lines of force. But the total force in this direction may be regarded as the resultant of

two weaker forces, one horizontal, and the other vertical. In Fig. 82 nI represents the magnitude and direction of the force acting on a single north-seeking pole, n. If the iron is held horizontally the degree of magnetisation will depend directly upon the magnitude of the horizontal force nH; if held vertically, the magnetisation will depend upon the magnitude of the vertical force nV.

But $\frac{nV}{nH} = \frac{HI}{nH}$ = the tangent of the angle of Dip (HnI), p. 108.

The degree of magnetisation in these two positions may be compared by comparing the forces which the iron exerts on a magnetometer needle, assuming that the distance between the iron and the needle is the same in each case.

EXPT. 63.—Use a fairly thick piece of galvanised iron (about 30 cms. long and 2 cms. wide). Place the magnetometer with its cm. scale at right angles to the meridian. Test the iron to verify its freedom from permanent magnetisation. Hold the iron vertically with its lower end touching the scale of the magnetometer, and about 7 cms. distant from the needle. Note the deflection and the distance. Remove the iron and carefully demagnetise it by tapping while it is held east and west. Hold the iron horizontally in the meridian with its northern end at the same distance from the needle as before. Note the deflection. Reverse the ends of the iron and repeat the observations. Bear in mind that the forces are proportional to *the tangent of the angle of deflection.* Tabulate the results as follows:—

	Vertical Position.		Horizontal Position.		$\frac{(2)}{(4)}$ = Tangent of Angle of Dip.	Dip.
	(1) Deflection.	(2) Tangent of (1).	(3) Deflection.	(4) Tangent of (3).		
1.						
2.						

The magnitude of (4) will be necessarily small if a rough magnetometer is used, but the experiment will be sufficiently accurate to explain how the phenomenon of Induction may be applied to the determination of the angle of Dip.

The forces which have been compared in this experiment are usually termed the *Horizontal Intensity* and the *Vertical Intensity* of the earth's field. It is clear, from Fig. 82, that as the angle of Dip increases so the Horizontal Intensity diminishes; consequently, in a position of high latitude a compass-needle will oscillate *less* rapidly than when near to the equator. On the contrary, it might appear that, since in the former case the needle is nearer the magnetic pole of the earth, the *total* intensity would be greater, and that this would compensate for the diminution of the Horizontal Intensity due to the change in the angle of Dip. This is so to a slight extent, but the rate at which the Total Intensity increases is small compared with the rate at which the angle of Dip increases.

Simple Hypothesis of Terrestrial Magnetism.—When Dr. Gilbert conceived the idea that the earth itself was a great magnet, he endeavoured to reproduce the phenomena of terrestrial magnetism on a small scale. He made a small sphere out of lodestone, which he called a *terrella*. He poised small magnets on the surface of his terrella, and observed how they pointed towards the poles of the lodestone, and remarked the general similarity between the behaviour of the needles in his experiment and that actually observed when they were acted upon by the earth's field.

Both Declination and Dip may be roughly explained as being due to a huge imaginary bar-magnet passing through the earth's centre and slightly inclined to its axis, so that one end approaches the earth's surface at Boothia Felix and the other end approaches the surfaces near to the south geographical pole at a point which has not yet been explored. At these points the dip-needle stands vertically, and they are called the *magnetic poles* of the earth. The directions of the lines of force of such a magnet would approximately coincide with the directions in which a dip-needle is observed to point. In Fig. 83 N*g* and S*g* are the geographical poles, S*m* and N*m* the magnetic poles of the imaginary bar-magnet which is

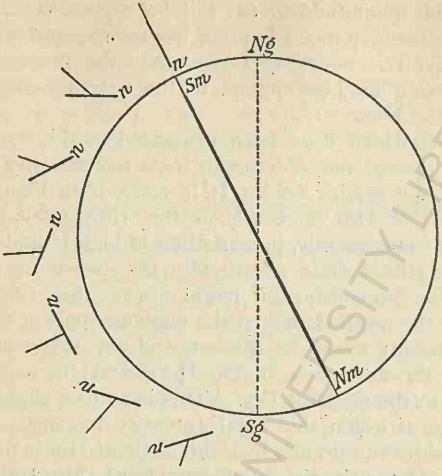


FIG. 83.—Terrestrial magnetism due to an imaginary magnet

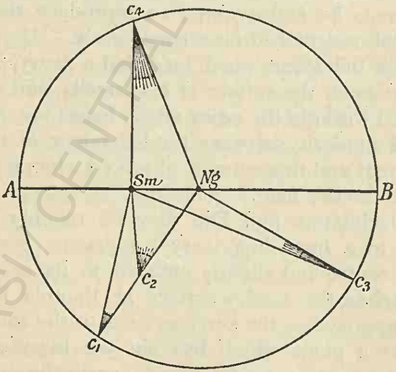


FIG. 84.—Plan of the northern hemisphere.

influencing a dip-needle placed at various points on the earth's surface.[1] Fig. 84 represents a plan of the northern hemisphere.

[1] Compare Fig. 83 with Fig. 58.

Ng is the north geographical pole, and Sm is the south magnetic pole. At any point along AB the compass-needle will point due north, consequently AB is an agonic line. The angle SC_1N represents the declination at C_1. The angles SC_2N, SC_3N, and SC_4N represent the declination at the points C_2, C_3, and C_4 respectively.

But the distribution of terrestrial magnetism is more complex than this. To mention one point only where the theory fails, the student will notice that it only accounts for one agonic line, which extends completely round the earth, whereas there is also the agonic oval in Siberia.

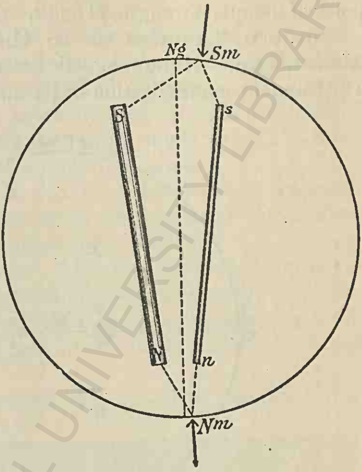


FIG. 85.—Terrestrial magnetism due to two imaginary magnets.

The earth's magnetism might be better represented by supposing that there are *two* magnets within the earth, one much stronger than the other, and situated relatively to each other as shown in Fig. 85. The dip-needle will be vertical at the points Sm and Nm, and will thus locate what are termed the magnetic poles.

Fig. 86 represents a plan of the northern hemisphere. Imagine A_1N to be the agonic line passing through America, and that a compass-needle is conveyed in an easterly direction starting from a point on the line A_1N. Its declination will become *westerly*, and gradually increase and again diminish as it approaches the agonic line A_2N (situated near to the Caspian Sea). The declination then becomes *easterly* for a short distance as far as the agonic line A_3N (which is the western arm of the Siberian oval). Inside the *oval* the declination is *westerly*, and the agonic line A_4N is the eastern arm of the Siberian oval. Between A_4 and A_1 there is a wide

area extending across the Pacific, in which the declination is *easterly*. The alternation of westerly and easterly declination is readily explained by the joint magnetic forces due to the two poles of unequal strength, S and *s*. (Compare Figs. 77 and 86.)

Modern Theories as to the cause of Terrestrial Magnetism.—If the magnetic state of the earth arises from a permanent magnetisation of its materials, it must be confined

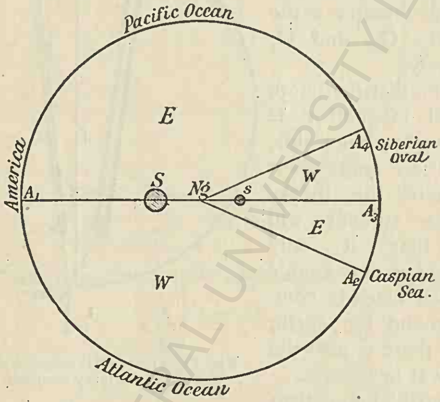


FIG. 86.—Plan of the northern hemisphere.

to the outer layers. The temperature increases as we descend towards the centre of the earth, and at a depth of twelve miles the temperature would be sufficient to render it red-hot. Under such conditions it is impossible for any permanent magnetisation to exist. Hence such magnetisation can only be skin-deep.

The student will remember that an electric current is capable of generating magnetisation in iron, and it is quite feasible to imagine that the earth's magnetism is due to a system of electric currents flowing through its mass. The high temperature of the interior would in no way interfere with the passage of electric currents through those portions where permanent magnetisation is impossible. It is suggestive towards a trustworthy theory that electric earth currents should be detected

simultaneously with those brief disturbances in the magnetic constants which are termed *magnetic storms*, and that these should occur simultaneously with brilliant displays of the *aurora* in the northern and southern hemispheres. Moreover, in each case, the luminous arc of the aurora has its centre coincident with the magnetic poles of the earth. There is every reason to believe that magnetic disturbances are largely influenced by causes which originate from outside the earth, and there is no absolute proof as to how much of the earth's magnetism is to be attributed to internal causes.

The ideas suggested on p. 117 are only offered as working hypotheses whereby the main facts of terrestrial magnetism may be impressed upon the mind of the student.

The Mariner's Compass.—The simplest form of mariner's compass consists of a magnetised needle fastened underneath a circular card, the upper surface of which is divided by radii into thirty-two divisions. These divisions are called *the points of the compass.*

The form of needle suggested by Dr. Gilbert consisted of a pair of thin bent needles with their ends united. This form is still adopted in many small vessels. The needle and card are supported on a sharp metal pivot by means of an agate cap which is fixed to the centre of the needle.

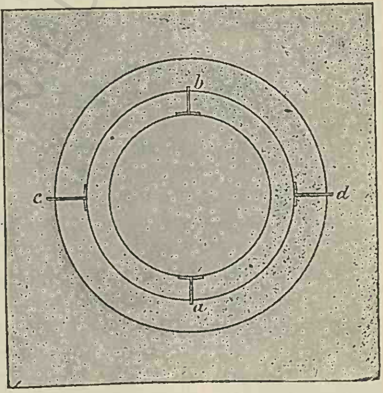


Fig. 87.—Gimbals.

In order to prevent the rolling of the ship from disturbing the compass out of the horizontal position, the circular box (made of brass or copper) containing the needle is supported on *gimbals*, which are represented in Fig. 87. The compass-box is pivoted on two axes, *a* and *b*, so as to turn freely inside a ring which is also capable of turning round the axis *cd* (at

right angles to *ab*). This arrangement allows the compass-box to remain horizontal in spite of the rolling and pitching of the vessel.

In the modern Admiralty standard pattern the needles consist of two pairs of parallel straight bars of flat clock-spring fixed with their breadth perpendicular to the card. The card consists of a thin disc of mica, 10 inches in diameter, with paper pasted on *each* side to prevent warping.

Lord Kelvin's pattern (known as Thomson's standard compass) contains eight thin steel needles, each two inches long.

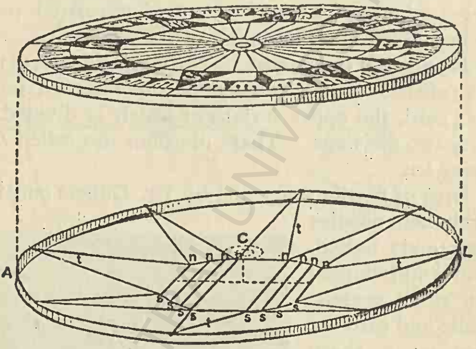


FIG. 88.—Mariner's compass (Lord Kelvin's pattern).
(From Aldous' *Elementary Course of Physics.* Macmillan and Co., Ltd.)

This pattern is represented in Fig. 88. The needles are fastened together like a rope-ladder on two silk threads, and slung from a light aluminium ring by silk threads. This rim is connected by thirty-two threads to a small aluminium disc with a sapphire cup in the centre which rests on an iridium point. The rim carries the paper ring, on which is printed the points of the compass. The entire arrangement weighs about 11 grams.

Astatic Needles.—It is sometimes desirable to use a magnetic needle which, when suspended, is unacted upon by the earth's field. If a single magnetised needle is bent so as to form three sides of a square, and is suspended as shown in Fig. 89 (i.), the forces acting on n and s will be equal and opposite in direction, and the needle will remain at rest in

any position. Such an arrangement is termed an *astatic needle.*

A more useful method in practice is that originally devised

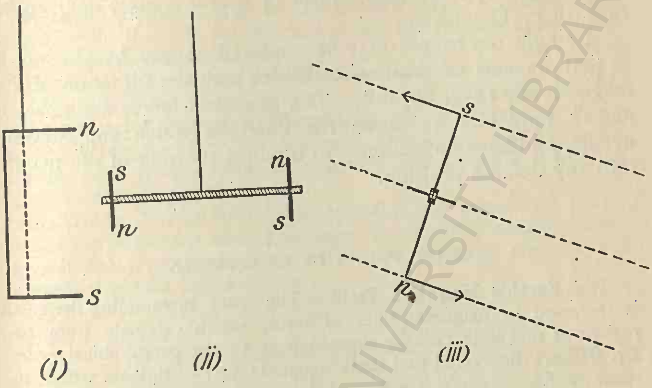


FIG. 89.—Astatic needles and astatic pair.

by Nobili. Two magnetised needles, which are as identical as possible in dimension and degree of magnetisation, are rigidly fixed together in the manner shown in Fig. 90. When freely suspended in the earth's field, the forces acting on the lower needle are neutralised by those acting on the upper needle. In practice it is almost impossible to obtain two magnets absolutely identical in every respect, but it is easy to obtain an arrangement which is sufficiently astatic for experimental purposes; it is usually termed an *astatic couple* or *astatic pair.*

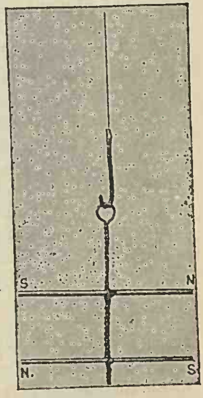


FIG. 90.—An astatic pair.

EXPT. 64.—Make an astatic pair by breaking a magnetised knitting-needle into halves. Join them together in the relative positions shown in Fig. 90 by means of twisted copper wire. Suspend the pair by means of silk fibre. Notice how slowly the pair vibrates

to and fro in the earth's field. Reverse the poles of the lower needle, and observe how much more rapidly the pair vibrates when suspended.

Fig. 89 (ii.) represents a form of astatic couple devised by Prof. S. P. Thompson.

A single dip-needle may be rendered astatic by placing it so that its axis of rotation coincides with the direction of the magnetic dip (Fig. 89, iii.). The magnetic forces acting on *n* and *s* only tend to strain the bearings which support the needle, and have no tendency to produce rotation of the needle into any definite position.

Chief Points of Chapter IX

The Earth's Magnetic Field.—The space surrounding the earth is traversed by magnetic lines of force, which originate from two regions of magnetic polarity situated near to the geographical poles. **Dr. Gilbert** discovered that these magnetic forces originate within the earth itself.

The Magnetic Meridian at any point is the vertical plane passing through the axis of a compass-needle placed at that point.

The Declination at any locality is the *angle* between the magnetic meridian and the geographical meridian.

The Declination is not the same at all points of the earth. It is 16° 16′ W. at London, 9° 36′ E. at Sydney, and *nil* at St. Petersburg.

The Declination is subject to a slow *secular change*. About 320 years are required for a complete cycle of changes to take place.

Isogonic Lines are lines drawn on any geographical map connecting localities of equal declination.

Agonic Lines are lines connecting localities of no declination.

The Dip at any locality is the angle between the axis of a magnetised needle, which is free to move in the vertical plane of the meridian, and the horizontal line through its point of support.

The Dip was first observed by Robert Norman in 1576.

The degree of Dip is not the same in all localities; it is 67° 11′ in London.

Isoclinic Lines are lines drawn on any geographical map connecting localities of equal Dip.

The Magnetic Equator is the line of *no Dip* which encircles the globe near to its geographical equator.

The Magnetic Poles of the earth are localities where the Dip is equal to 90°. Sir John Ross (in 1831) located the northern magnetic pole in Boothia Felix.

The Dip is subject to a slow *secular change.*

The Directive Action of the Earth's Field.—The effect of the earth's field on a magnetised needle free to move is *directive* but *not translatory.*

Magnetic Induction due to the Earth's Field.—A piece of soft iron held with its axis in the direction of the earth's lines of force will become magnetised by induction.

The Total Intensity of the Earth's Field may be resolved into two components—the *Horizontal* and the *Vertical Components.*

Hypothesis of Terrestrial Magnetism.—A simple working hypothesis is to imagine that there are two immense magnets within the earth not quite parallel to each other, and approximately coinciding with the earth's geographical axis.

An Astatic Needle is the term applied to any magnetised needle which, when suspended, is unacted upon by the earth's magnetic field. A combination of magnetised needles showing the same characteristic is termed an *Astatic Couple* or *Pair.*

Questions on Chapter IX

1. Define *Declination*, and describe a simple experimental method of determining it.

2. Give a brief account of the way in which the Declination varies at different parts of the earth's surface. What are *Isogonic* and *Agonic Lines?*

3. Given a magnet and the means of suspending it. How will you determine (1) the magnetic meridian, (2) in which direction *North* lies? It is assumed that you do not know which end of your magnet is a north and which a south pole. (1891.)

4. A strip of steel is bent about the middle point, so that the halves are inclined to each other at a right angle. It is then magnetised so that its extremities are south poles and the angular point a north pole, and is placed on a flat piece of cork floating in a basin of water. How will it set? (1896.)

5. A horse-shoe magnet lies flat on a sheet of brass which is supported by strings in such a way that it turns about a vertical axis, but always remains horizontal. How will it place itself? (1893.)

6. A bar-magnet is laid on a table perpendicularly to the magnetic meridian, and so as to point to the centre of a compass-needle. Describe and explain the behaviour of the needle. (1893.)

7. A rod of iron, AB, held vertical with the end B downwards, is smartly tapped with a mallet. When turned into a horizontal position and brought near to a compass-needle, the end B repels the north pole of the needle at a distance of four inches, but attracts it when the distance is reduced to one inch. Explain this. (1890.)

8. A large soft iron rod lies on a table in the magnetic meridian, and a dipping needle is placed at some distance and at about the same level (1) due south, (2) due north of it. How will the magnitude of the angle of dip be affected in each case? (Neglect any inductive action between the needle and the bar.) (1890.)

9. A tall iron mast is situated a little in front of the compass in a wooden ship. Explain the nature of the compass error when the ship is sailing in an easterly direction (1) in the northern, (2) in the southern hemisphere. (1891.)

10. A rod of iron when brought near to a compass-needle attracts one pole and repels the other. How will you ascertain whether its magnetism is permanent or is due to temporary induction from the earth? (1891.)

11. An iron rod held vertically is tapped with a mallet. The upper end is found to repel the south pole, and attract the north pole of a compass-needle. The rod is now quietly inverted and the same end (which is now the lower) is tested again. It is then tapped and once more tested. State what results you would expect, and explain them. (1892.)

12. A dipping needle can oscillate in the magnetic meridian. A long bar of soft iron held horizontally in a north and south direction is brought near to it from the south. How is the inclination of the needle to the horizon affected as the distance between it and the bar is gradually diminished? (1892.)

13. A bar of soft iron is held vertically over the centre of a dip-needle, but not near enough to have magnetism induced in it by the needle. Is the dip increased or diminished by the presence of the bar, and would the result be the same in each of the two hemispheres? (1895.)

14. A rod of iron free from magnetism is suspended by a string so as to turn in a horizontal plane, and the string is twisted until the rod rests at right angles to the magnetic meridian. Explain the behaviour of the rod if a magnet is brought near to it from a distance in such a way that its axis is nearly in the line passing through the centre of the rod and perpendicular to it. (1898.)

15. A bar of soft iron lies on a table at right angles to the magnetic meridian, and a compass-needle is placed at some distance from the bar with its centre on the axis of the bar produced The end of the bar nearest to the needle being kept in the same position, the bar is then turned round, upon the table, until it is parallel to the magnetic meridian, the fixed end of the bar being to the south. Describe the behaviour of the compass (1) before, (2) during the rotation of the bar. (1896.)

PART II

STATICAL ELECTRICITY

CHAPTER X

PRELIMINARY EXPERIMENTS

Apparatus required.—Drying oven. Vulcanite rods and glass rods. Suspending stirrup. Flannel. Fur. Clothes-brush. Fragments of paper. Wooden lath and round-bottomed flask. Bunsen-burner. Insulated metal tube or plate. Electroscope. Pieces of paper, dry glass, cotton and silk threads, paraffin-wax, etc. Oil. Ebonite rod with flannel cap. Squares of smooth and rough glass.

EXPT. 65.—Rub a rod of vulcanite on the coat-sleeve. Notice that the rod has acquired the peculiar property of picking up small fragments of paper, cork, or cotton fibre when brought near to them. Also notice that actual contact is not necessary, but that the effects take place when the rod is still some distance away.

Heavy bodies are attracted in a similar manner, but the effect only becomes evident when such bodies are supported in such a manner as to allow almost perfect freedom of motion.

EXPT. 66.—Balance a long wooden lath (*e.g.* a metre scale) on an inverted round-bottomed flask. Bring a piece of vulcanite which has been rubbed as in Expt. 65 near to the end of the lath, and notice the attraction which takes place.

The ancient Greeks observed the same phenomena of attraction when *amber* was rubbed with wool. This is mentioned in the writings of Thales of Miletus (B.C. 600). Our word *electricity* is derived from the Greek word for *amber* (ἤλεκτρον). Until the year 1600 A.D. it was thought that amber was the only substance capable of exhibiting these phenomena, but in that year Dr. Gilbert found that many other substances were capable of affording similar results, *e.g. resin, sulphur, glass*, etc., and these substances he called *electrics.*

When a substance is rubbed with a suitable material, and is then found to possess the property of attracting light objects, it is said to be **electrified** (or, *to possess a charge of electricity*).

In order to produce these effects of attraction actual *force* is required, and this force can only be due to some peculiar condition which the substance has acquired when electrified. Such forces are called *electric forces.* The space around the substance, extending as far as the forces are evident, is called the *electric field.*

Are these forces mutual? *i.e.* if an electrified body attracts an unelectrified body, does the reverse also hold good?

EXPT. 67.—Suspend a rod of vulcanite which has been rubbed on the coat-sleeve (or with flannel) in a wire stirrup hanging from a thread of tinsel or silk. Hold the hand near to it. Notice how the rod is attracted towards the hand.

EXPT. 68.—Rub a piece of well-dried flannel[1] (or brown paper) with a clothes-brush, and notice how it will cling to the walls of the room.

Hence the forces of electric attraction are mutual, just in the same way that the forces of magnetic attraction between a magnet and a piece of soft iron are mutual.

[1] **A Simple Form of Drying Oven.**—It is often expedient to artificially dry the appliances used in experiments on Statical Electricity. A portable drying oven may be constructed in the following manner. Fill a shallow baking-tin (about 40 cms. × 20 cms.) with sand, and cover it with a sheet of thin iron (about 40 cms. × 35 cms.) bent into the form of a semicircle, so as to form a hood over the sand-bath. The bath is supported on tripods, and heated by Bunsen-burners placed underneath. Glass rods may be placed in the sand, and paper, flannel, silk, etc., may be spread over the hood.

How does an electrified body behave towards another electrified body?

EXPT. 69.—(i.) Suspend an electrified rod of vulcanite, and bring near to one end of it another rod of vulcanite which has been similarly electrified. Notice the *repulsion* which takes place.

(ii.) Repeat Expt. (i.), using, instead of the vulcanite, glass rods which have been dried in the oven and rubbed with silk. Notice the *repulsion.*

(iii.) Suspend an electrified rod of vulcanite. Bring near to it a rod of glass which has been rubbed with silk. Notice the *attraction.*

These results were first observed by Du Fay, who endeavoured to explain the phenomena by assuming the existence of *two kinds of electrification*, which attract one another, while each repels itself. He termed the electrification generated on the glass *vitreous electricity*, and that generated on vulcanite *resinous electricity.* At a later date it was found that the kind of electrification generated depended on the substance used as a rubber, *e.g.* glass when rubbed with *fur* becomes charged with *resinous* electricity.

EXPT. 70.—Suspend an electrified rod of vulcanite. Bring near to it a rod of glass which has been rubbed with fur. The *repulsion* indicates that the charge on the glass must be *resinous.*

In consequence of such results the names *vitreous* and *resinous* were abandoned in favour of the terms *positive* and *negative*, which were first introduced by Franklin.

Theories of Electricity.—Attempts have been made to explain the cause of these phenomena. When two bodies are rubbed together the electricity which may be generated cannot be of the nature of a substance (solid, liquid, or gaseous), for an electrified body weighs just the same when electrified as it does when unelectrified.[1] The difference between these two conditions may be more satisfactorily compared to the differ-

[1] Nevertheless the behaviour of an electric charge so closely resembles that of a fluid contained in a vessel or pipe that the early nomenclature is still retained; for example, "the electric fluid," "an electric current," "the flow of electricity," etc., are expressions which are frequently made use of.

ence between a clock-spring when wound up and when run down (*i.e.* when in a condition of strain and when free from strain), or to a piece of elastic thread when stretched and when unstretched (*i.e.* when in a state of tension and when free from tension),—the difference is simply one of physical condition. But the question still remains unanswered as to where the seat of the tension or strain exists, and we may not assume that this is necessarily confined within the limits of the electrified body.

Two theories were propounded many years ago which may be briefly referred to at this stage. Symmer suggested a *two-fluid theory;* according to it there are two electric fluids of opposite kind present in all substances, and the process of electrification involves the complete or partial withdrawal of one of them. At a later date Franklin suggested the more feasible *one-fluid theory*, according to which all unelectrified bodies contain a normal amount of an electric fluid; the process of electrification involves either an increase or a diminution of the amount of the electric fluid present. In the former case the body was said to be *positively* charged, and in the latter case *negatively* charged. Though no proof exists for the statement that a positively-charged body contains more electricity than a negatively-charged body, yet the nomenclature adopted by Franklin is still used, and the accepted rules are that—

(i.) *Glass rubbed with silk is positively charged.*

(ii.) *Vulcanite* (*or resin*) *rubbed with fur* (*or flannel*) *is negatively charged.*

(iii.) *Bodies with like charges repel, and bodies with unlike charges attract each other.*

(iv.) *A charged body always attracts an uncharged body.*

Do all Substances become electrified when rubbed?—Dr. Gilbert found that many substances, chiefly metals, did not show any signs of electrification when rubbed—these he called *non-electrics.* We now know that this depends upon the manner in which the experiment is conducted.

EXPT. 71.—Suspend an electrified rod of vulcanite. Bring near to it a second electrified rod of vulcanite. Notice the repulsion. Pass the latter rod *gently*[1] through

[1] If vulcanite is passed *vigorously* through the hand it is $-$ly electrified.

the hand, taking care that all parts of the rod are touched by the hand, and again test. Attraction shows that the rod is no longer charged. Again electrify the rod, and afterwards pass it through the flame of a Bunsen-burner. Attraction shows that the rod has lost its charge in this case also.

The hand and the flame have *conducted* the charge away—they are what are called **conductors.** The vulcanite can-

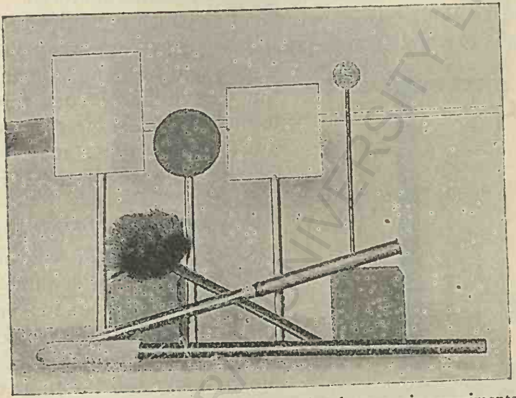


FIG. 91.—A group of simple appliances for electrostatic experiments.

not be a conductor, since the charge on one portion of its surface is not conveyed to the end which is held in the hand of the experimenter.

Vulcanite, and all substances which Dr. Gilbert called *electrics*, are now termed **insulators.** If metals are conductors of electricity, then it is readily seen why Dr. Gilbert was unable to detect any electrification on the surface of a metal which had been rubbed; any charge which the metal might acquire would be immediately conducted away by the hand in which the metal is held.

EXPT. 72.—Fix a short brass or iron tube (or a square piece of sheet brass or zinc) on the end of a rod of vulcanite, or on the end of a piece of clean dry glass-tubing (Fig. 91). Flick the metal with a piece of fur.

Bring it near to a suspended rod of vulcanite which has been electrified. Notice the repulsion. The metal is evidently charged negatively. A flat sheet of metal will show the same effect.

In this experiment the charge on the metal cannot escape, because it is separated from the hand by a length of insulating material. The metal is said to be *insulated.* By adopting similar precautions we can prove that almost all substances become electrified when rubbed with suitable material.

Electroscopes.—Any appliance which is so devised that, by means of it, it becomes possible to detect very weak electrical forces, and also small changes in the magnitude of such forces, is termed an *electroscope.* Any of the following types may be used for the purpose of these experiments:—

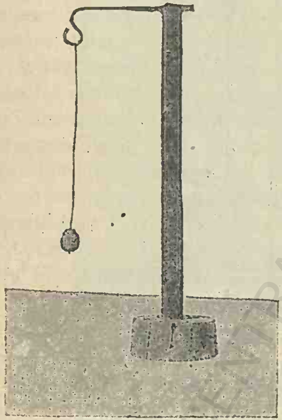


FIG. 92.—Pith-ball electroscope.

(i.) *Pith-ball Electroscope* (Fig. 92).—Fix a rod of vulcanite to a flat cork (or other suitable base) so that the rod stands in a vertical position. Bend the end of a piece of stout copper wire (5 cms. long) into a hook, and fasten it to the top of, and at right angles to, the rod. From the hook suspend a gilt pith-ball by means of very thin copper wire (or cotton thread). It is important to avoid sharp metal points, a difficulty which is readily overcome by fusing the ends of the wires in a blowpipe flame or by covering the ends with a spot of sealing-wax or soft wax. A pith-ball is satisfactorily "gilded" by moistening the surface with weak gum and, when nearly dry, rolling it in gold-leaf (Dutch-metal leaf or aluminium leaf are satisfactory substitutes for gold-leaf).

(ii.) *Aluminium-disc Electroscope* (Fig. 93).—A larger electroscope than the pith-ball type is often desirable for class purposes. The following arrangement is convenient in such cases. Pivot a piece of copper wire (about 20 cms. long) on a

vertical needle, in the same manner as represented in Fig. 4. Attach to one end of the wire a disc of aluminium (or thin copper) foil, about 5 cms. diameter, and so that the disc is

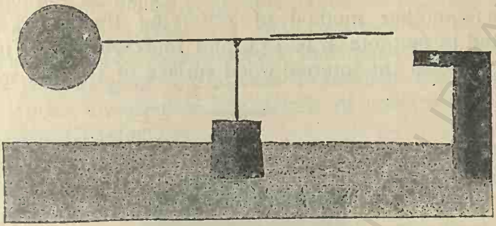


FIG. 93.—Aluminium-disc electroscope.

vertical. In order that the electroscope may take up a definite position of rest, fix a magnetised needle (with blunt point) to the other end of the wire, and adjust its position so that it acts as a counterpoise to the metal disc. The magnetised needle may be made to take up a definite position by placing a bar-magnet in a convenient position near to it.

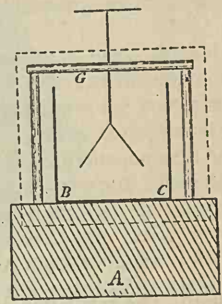


FIG. 94.—Gold-leaf electroscope for lantern work.

(iii.) *The Gold-leaf Electroscope* (Fig. 95).[1]—This is a practical application of the fact that two similarly charged bodies repel one another. A simple form of this instrument may be made from a cigar-box (Fig. 95) in the following manner:—Remove the top and bottom of the box and cut away the lower portions so as to leave sufficient open space for glass plates (photographic ½-plate is a convenient size) to slide in shallow grooves cut in the wood-work. Changes in the divergence of the leaves are

[1] Fig. 94 represents a simple electroscope suitable for lantern projection. A is a block of wood (7 × 4 × 4 cms.), BC is a strip of zinc (15 × 2 cms.) bent twice at right angles. The thick wire carrying the leaves is attached to a horizontal glass-rod, G, by means of sealing-wax. The dotted lines indicate two plates of glass fixed at the front and back of the wooden block to protect the leaves from air-currents.

observed readily if the glass surface is divided into squares by means of ink-lines, which are ruled readily in Indian ink on the dry gelatine film of a photographic plate from which the silver salts have been removed by solution in sodium hyposulphite: another method of observing the divergence is suggested in footnote 2, p. 133, and represented in Fig. 129, p. 189. Cover the internal wood surface of the box with tin-

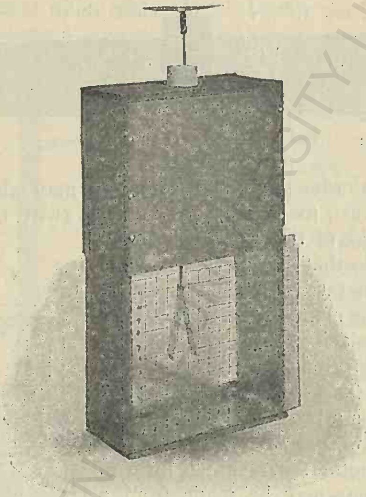


FIG. 95.—A simple type of gold-leaf electroscope.

foil. The insulation is obtained most satisfactorily by means of a plug of sulphur, supported in a circular hole bored in the end of the box. The plug is prepared by pouring liquid sulphur, which has been melted *slowly*, so as to form a clear straw-coloured liquid, into a paper mould made by wrapping paper round a cork; the lower end of the mould is closed by a disc of cork pierced by a straight piece of thick copper wire which will subsequently carry the gold leaves (the paper should be cut away from the plug while it is still hot). Taper off the lower end of the wire to a flat edge, and solder to it a rectangular strip of sheet copper. Support a metal disc on

the upper end of the wire by means of a short length of metal tube, or a closely wound spiral of wire, soldered to the centre of the disc. The leaves may be of gold or of Dutch-metal leaf—the former is more efficient but more difficult to handle. Cut two leaves, each about 5 cms. × 1 cm., and attach to the lower end of the wire which has been previously moistened with a *minimum* quantity of weak gum, and allowed to become nearly dry.[1]

The theory involved in the details of construction will be discussed in Chapter XII.

When a charge of electricity is given to the metal disc, the leaves will diverge, and the degree of divergence depends upon the magnitude of the charge.[2]

Classification of Substances as Conductors or Insulators.—We have found that the hand, a flame, and metals are conductors, and that sealing-wax and glass are insulators. With the aid of an electroscope the conducting or insulating power of any substance can be roughly determined. With a gilt pith-ball electroscope the following experiments may be made:—

EXPT. 73.—(i.) Rub a piece of vulcanite with flannel. Bring it near to the pith-ball. The ball is attracted, and after rolling about slightly over the surface of the vulcanite acquires a charge of the same kind and is consequently repelled. Touch the thick copper wire with the finger. The ball is at once attracted again by the vulcanite, showing that the charge on the ball has escaped through the finger.

(ii.) Repeat the experiment, but touch the thick wire with a strip of paper instead of with the finger. The repulsion slowly diminishes and the pith-ball is finally attracted once more. This shows that the charge has *slowly* escaped through the paper.

[1] Dutch-metal (or gold) leaf may be cut in the following way:—Spread a sheet of thin well-glazed paper on a sheet of glass, and lay the metal leaf on the paper. Cover the leaf, except a strip of the width required, with a second sheet of paper. Cut off the strip by means of a sharp razor, using the edge of the paper as a guide. Practice is required in order to determine the requisite pressure and speed of cutting, since both of these must be observed in order to prevent the leaf from tearing.

[2] The degree of divergence may be more accurately observed by placing a circular scale just behind the leaves. The paper-scale is mounted on sheet-mica, and is supported vertically on a rod of sealing-wax.

(iii.) Repeat the experiment, using *dry* glass instead of paper. The repulsion remains unaltered, showing that the glass is a non-conductor (*i.e.* an insulator).

Repeat the experiment with the following substances:—Any metal wire, cotton thread, charcoal, wood, stone, wet glass, dry silk thread, wet silk thread, sulphur, shellac, wool, paraffin-wax, silk thread dipped in oil, vulcanite, etc. etc.

In this manner the following classification may be obtained:—

Conductors—metals, the body, water, charcoal.

Partial Conductors—paper, cotton, wood, stone.

Insulators—glass, sealing-wax, shellac, vulcanite, silk, wool, sulphur, oils.

It is evident from these results that if a conductor is required to retain a charge of electricity it is necessary to insulate it on a support of dry glass, sealing-wax, or vulcanite (or to suspend it by silk threads). In some cases the *insulator* forms a convenient handle by which the conductor may be conveyed to different positions.

Effects of Moisture.—An important result to notice is the effect of even a thin film of moisture on the surface of any material which, if dry, would be an insulator. It is absolutely necessary that all apparatus used in electrostatic experiments should be quite dry; and it is for this reason that a damp atmosphere often renders it difficult to successfully carry out such experiments. Glass is particularly sensitive to a moist air. This liability is lessened by previously boiling the glass in water so as to remove any alkali from the surface (alkali tends to absorb moisture). A safer precaution is to paint the surface of any glass insulating supports with shellac varnish or with a solution of sealing-wax dissolved in methylated spirit.

These experiments also explain the wide difference in the results obtained by touching with the hand a *charged conductor* and a *charged insulator*. In the former case not only is the charge removed from the point actually touched, but the charge from distant points of the conductor are conveyed by the conductor itself to the point where the finger is touching. In the case of a charged insulator the charge is only conveyed away from the locality actually touched; the charge at a neighbour-

ing point is separated from the finger by insulating material, and consequently remains undisturbed. Thus, if an electrified rod of vulcanite is to be discharged by means of the hand, it must be drawn carefully through the closed fingers so that *all* points of the surface may thereby be brought into contact with the hand.

Both kinds of Electrification are produced simultaneously.—When glass is rubbed with fur it acquires a negative charge of electricity. Does the fur acquire any charge in the process? and if so, is it positive or negative? To answer this question by experiment it will be necessary to carefully insulate the fur. This may be done by attaching a disc of cardboard to the end of a rod of vulcanite and covering the disc with a piece of fur of about the same size. Mount a small square of glass on a similar handle (Fig. 91).

EXPT. 74.—Holding the glass and the fur by the handles, rub them together. Keeping them in contact, bring them near to an uncharged pith-ball. No effect is seen. When the fur is removed, the glass alone attracts the pith-ball. The fur alone will also attract it. Both the glass and the fur are evidently charged; but since they have no effect when together, the charge on the fur must be equal and opposite to the negative charge on the glass. To verify that the fur is positively charged, bring it near to a pith-ball charged positively and notice the repulsion.

EXPT. 75.—Another method of proving the same result is to place a loose-fitting flannel cap, which is attached to one end of a long silk thread, over the end of a vulcanite rod (Fig. 91). Twist the thread round the cap and pull the thread so as to make the cap rotate round the end of the rod. As long as the cap remains on the rod no electrification can be detected. If the cap is removed (without touching it with the hand, but carefully supporting it by means of the silk thread) both will be found to be electrified.

These experiments prove that **when electrification is produced by friction the two kinds of electricity are produced in equal quantity.**

Frictional Order.—A pith-ball charged negatively is

attracted by a positively-charged body, and also by an uncharged body. Hence, when *attraction* takes place it is not a conclusive proof that the body is charged in any way. If the pith-ball *is* charged, *repulsion* is the only sure test of electrification. For example, if we observe that a − ly charged pith-ball is attracted, it is not safe to conclude that the body is charged + ly. It is advisable, in such a case, to discharge the pith-ball and re-charge it + ly by means of a glass rod rubbed with silk; *repulsion* will then conclusively prove that the body is charged + ly. By adopting this precaution, various substances may be tabulated in such a sequence that any one of them will be charged + ly when rubbed with one lower on the list, but − ly when rubbed with one higher on the list.[1]

Frictional order :—*Fur*, *flannel*, *shellac*, *sealing-wax*, *glass*, *paper*, *silk*, *rough glass*, *the hand*, *metals*, *sulphur*, *ebonite*.

Glass electrified by rubbing with Glass. EXPT. 76. —Two smooth pieces of flat glass do not become electrified when rubbed together. But if smooth glass is rubbed with a piece of *matt glass* it is found that the former is + ly charged and the latter − ly charged.

This result suggests that electrification does not necessarily depend upon any chemical difference in the substances used, but that a physical difference in the surfaces of the substances is sufficient to allow electrification to be produced.

CHIEF POINTS OF CHAPTER X

Preliminary.—Many substances, when rubbed with a suitable material, are found to possess the property of attracting light objects. They are then said to be *electrified*.

[1] Considerable care is required in using glass plates or rods in these experiments. Without any evident reason it will sometimes appear that the glass is − ly charged although rubbed with silk. If both have been dried in the sand-oven, the glass will be + ly electrified; but if the glass has been dried by passing it several times through a Bunsen-flame it will be charged − ly when rubbed with silk. It has been suggested that this is due to the flame removing the thin film of air condensed on the surface of the glass. This contradictory result may be verified by using a silk pad mounted on a sealing-wax handle (see Fig. 91). If the rods are allowed to become *quite cold* and then warmed again in the *drying oven*, they will recover their normal property of giving + ve electrification.

The electrification of amber by this method was known to the ancient Greeks. The word "electricity" is derived from the Greek word for "amber." An electrified body exerts *force* on neighbouring bodies.

Electrical Forces are Mutual.—An unelectrified body exerts *force* on an electrified body.

Electrical Attraction and Repulsion.—When an electrified body exerts force on another electrified body sometimes an *attraction* and sometimes a *repulsion* is observed.

Nature of Electricity.—Electricity is not a fluid, nor does it possess the character of *matter* in any form. Electrification is rather a *physical condition* which may be assumed by a body in the same manner that a piece of elastic assumes a condition of tension when it is stretched.

Theories of Electricity.—(i.) *Symmer's Two-fluid Theory*, according to which there are two electric "fluids," of opposite kind, present in equal quantities in all substances.

(ii.) *Franklin's One-fluid Theory*, according to which all substances contain a normal amount of "electricity." The process of electrification involves either an increase or a diminution of the electrical charge present. These conditions are distinguished by the terms *positive* and *negative*.

Fundamental Rules.—(i.) *Glass rubbed with silk is positively charged.*

(ii.) *Vulcanite rubbed with fur (or flannel) is negatively charged.*

(iii.) *Bodies with like charges repel, and bodies with unlike charges attract, each other.*

(iv.) *A charged body always attracts an uncharged body.*

An Electroscope is an appliance for detecting electrical forces, and also small changes in the magnitude of such forces.

Conductors and Insulators.—All substances which allow an electrical charge to extend freely through their mass are termed *Conductors—e.g.* metals, the body, water, etc.

All substances which do not allow the charge to extend freely are termed *Insulators—e.g.* glass, sealing-wax, paraffin-wax, ebonite, silk, oils, etc.

Some bodies occupy an intermediate position, and are termed *Partial Conductors.*

Both kinds of electrification are produced simultaneously and in equal quantity when two substances are rubbed together.

Frictional Order.—Substances may be arranged in the form of a list, such that any one of them will be charged +ly when rubbed with one lower on the list, but −ly when rubbed with one higher on the list.

Questions on Chapter X

1. How would you prove that an electrified body is attracted by an unelectrified body?

2. Explain briefly the *two-fluid* and *one-fluid* theories of electricity, and state how the terms *positive* and *negative* are applied in each theory.

3. What evidence is there that electricity is not a fluid? What does electricity more closely resemble?

4. How would you show that a brass rod is capable of being electrified? Explain why on rubbing a brass rod and a glass rod the latter only ordinarily appears to be electrified by the friction. (1898.)

5. State the disadvantages of glass as an insulator, and describe the best means of overcoming them. (1895.)

6. Describe a simple experiment to show that a piece of glass, which is an insulator when cold, will conduct a current when heated sufficiently.

7. How would you prove to a class that there are two kinds of electricity? (1888.)

8. A rod of sealing-wax is rubbed with dry flannel. An uncharged pith-ball suspended by a silk thread is attracted when the sealing-wax is brought near to it, but is unaffected by the flannel. Would you conclude from this experiment that when sealing-wax and flannel are rubbed together the sealing-wax only is electrified? Give reasons for your answer. (1888.)

9. How would you prove that glass and silk when rubbed together are equally and oppositely charged? (1894.)

10. Describe any experiment by which you could prove that when electrification of one kind is produced, the opposite kind is also produced in equal quantity. (1887.)

11. You are given a stick of sealing-wax, some dry paper, and some silk thread. How would you seek to determine the nature of the electrification which is developed on dry paper when rubbed with the finger-nails?

12. If you want to find out whether a body is electrified by seeing how it acts on an electrified pith-ball hung by a silk thread, why is it a surer test that the body is electrified if it repels the pith-ball than if it attracts it? (1881.)

13. An electrified pith-ball is hung by a cotton thread attached to a glass rod. An electrified rod of sealing-wax is found to repel the pith-ball at first, but the repulsion gradually diminishes, and finally becomes an attraction. What conclusion would you arrive at from this?

14. What is the simplest method of removing completely the charge from an electrified rod of sealing-wax? What precaution must be adopted if the hand is used for the purpose?

15. How would you transfer a charge from an electrified rod of sealing-wax to a gold-leaf electroscope, sufficient to produce a considerable divergence of the leaves?

16. Under what conditions is it possible to obtain a negative charge on a glass rod when rubbed with silk? Describe the experiment. How must you proceed in order to ensure a positive charge on the glass?

17. How would you charge a gold-leaf electroscope negatively by means of a piece of fur only?

18. A charged gold-leaf electroscope is required for a certain experiment, and the divergence of the leaves is observed to be greater than is required. How would you remove a portion of the charge without completely discharging the instrument?

CHAPTER XI

ELECTRIC FIELDS OF FORCE

Apparatus required.—Appliance for determining the direction of force in an electric field. Insulated metal spheres. Wimshurst machine.

In our experiments on Magnetism we have found that like poles repel and that unlike poles attract, that the space separating such poles is a field of force through which magnetic forces are acting in definite directions (called the lines of force), and that if we conceive these lines of force to have properties similar to those possessed by stretched elastic threads (viz. tending to contract lengthwise and to expand crosswise), it is possible to explain all the experimental phenomena observed.

In Chapter X. we have found that bodies with *like* electric charges repel, and with *unlike* charges attract, one another. Moreover, these forces are transmitted through the intervening space in a similar manner to that observed in magnetic phenomena. These analogous points suggest that an electrified body must be surrounded by an electric field, at all points of which it is capable of exerting electric force upon other bodies. If such a field of force exists, then the force at any point in it must necessarily act in a definite direction, which may be regarded as the direction of the electric lines of force at that point.

An Electric Field may consequently be composed of *electric lines of force*, in the same way that a magnetic field is composed of magnetic lines of force. If we give to the former those physical properties which have already been given to the latter,

we obtain a clear mental conception of lines of electric force traversing the space between oppositely charged bodies, and, in their tendency to contract, causing the two bodies to approach.

In forming such a hypothesis we transfer our thoughts from the charged bodies to the free space separating the bodies, and in so doing we adopt the methods of reasoning which were suggested by Faraday, who first drew attention to the important part which the medium plays in all electrical phenomena.

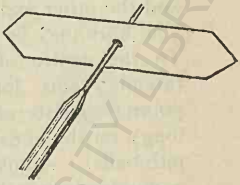


FIG. 96.

Unfortunately we are unable to experimentally map out a field of electric force either so satisfactorily or so simply as in the case of a magnetic field. Nevertheless, it is possible to construct a simple appliance which, when placed at different points in an electric field, will indicate the direction of the force at each point. In this manner, not only is the existence of the forces verified, but their general distribution in space is also proved to be comparable to that which has been found to exist in magnetic fields of force. One of the following devices may be used :—

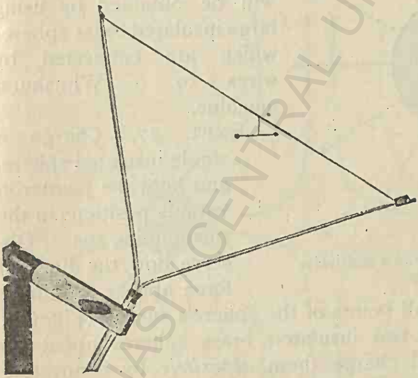


FIG. 97.—Apparatus described on p. 142.

(i.) Pierce a small circular hole through a piece of thin paper (3 cms. × 0.5 cm.). Pass a piece of drawn-out glass tubing through the hole, and allow the paper to be quite free to move (Fig. 96). Using the glass tube as a handle, bring the paper near to an

electrified body. The paper will point in the direction in which the electric forces are acting.

(ii.) Fix two long pieces of glass rod in a cork, and bend the rods so that they form a large V. Bore a hole in a small cork, so that it will fit tightly on the end of one of the rods. Attach one end of a silk fibre to this cork, and the other end to the free end of the other glass rod. The fibre may be tightened by rotating the small cork. To the centre of the fibre attach another short fibre (about 2 cms. long), which carries the *pointer*. The pointer consists of a piece of fine copper wire (5 cms. long), on the ends of which are threaded two small gilt pith-balls. Adjust the pith-balls so that the pointer hangs freely in a horizontal position (Fig. 97).

Whichever appliance is used, it will be found that the electric forces due to bodies charged directly by friction are weak, and far more satisfactory results will be obtained by using large insulated brass spheres which are connected by wires to a Wimshurst machine.

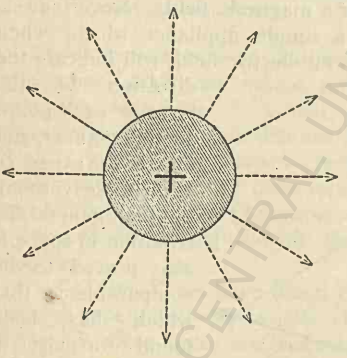


FIG. 98.—Lines of force due to a positively-charged sphere.

EXPT. 77.—Charge a single insulated sphere, and hold the pointer in various positions in the surrounding space. Observe how the lines of force appear to radiate outwards from all points of the sphere's surface (Fig. 98).

EXPT. 78.—Place two insulated brass spheres about 50 cms. apart, and charge them *oppositely* by connecting them to the poles of a Wimshurst machine. Verify the general distribution of the lines of force as shown by dotted lines in Fig. 99.

If the lines of force have properties similar to those possessed by stretched elastic threads, we at once see why oppositely charged bodies attract.

EXPT. 79.—Connect the two spheres to the *same* pole of

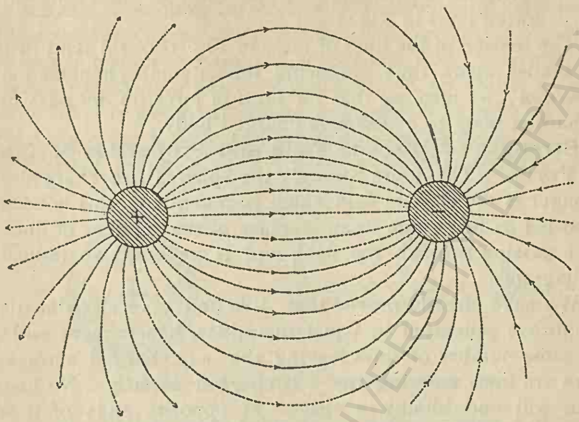


FIG. 99.—Lines of force due to two oppositely-charged spheres.

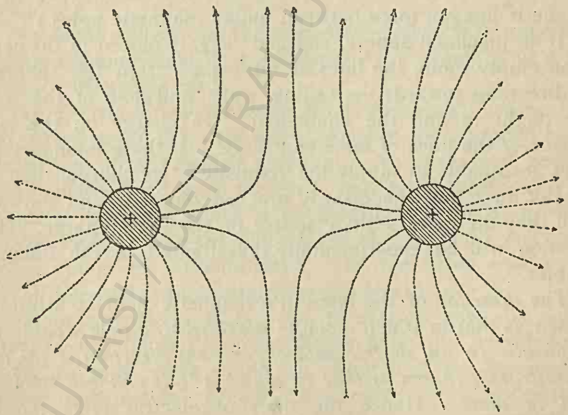


FIG. 100.—Lines of force due to two positively-charged spheres.

the Wimshurst machine, so as to give them *like* electric charges. It is advisable to connect the other pole of

the Wimshurst machine to the nearest gas- or water-pipe. Verify the distribution of the lines of force shown by dotted lines in Fig. 100.

The tension of the lines of force in Fig. 100 will tend to pull the bodies apart, thus producing the familiar phenomenon of *repulsion;* we also see that the lines of force do *not* pass from a charged body to a *similarly* charged body.

Strength of Electric Field and Properties of Lines of Force.—The more strongly the spheres are charged the stronger is the electric field which is generated; this is usually regarded as being due to an increase in the number of lines of force passing through the field, and is generally so indicated in diagrams.

We have already proved that + ve and − ve electrifications are always generated in equal quantities, hence there will be the same number of lines leaving the + ly charged surface as there are lines entering the − ly charged surface. No line of force will end blindly in space—at opposite ends of it will always be found equal quantities of opposite electrification, whatever its path may be. (This is exactly analogous to the magnetic lines of force between unlike magnetic poles.)

If an insulated sphere, charged + ly, is placed in the centre of an empty room, the lines of force pass from the sphere in all directions towards the ceiling, walls, and floor of the room. We ought to find the equivalent − ve charge on the latter surface, *if* the lines of force end there. If these boundary surfaces are unable to supply the requisite − ve charge, then the lines of force must necessarily proceed onwards and outwards until they do meet with a source of the − ve charge. This question will be experimentally investigated in the following chapter.

The *direction* of the force in a magnetic field is arbitrarily chosen as that in which a single *north-seeking* pole would tend to move. *In an electric field of force the direction of the force is arbitrarily chosen as that in which a + ly charged body will tend to move.* Hence the lines of electric force may be regarded as running *from* a + ly charged body *towards* a − ly charged body.

Electric Potential.—In Fig. 101 let A represent an insulated sphere + ly charged. Let v_1 represent a small + ly

charged sphere (which we will term a *test-charge*) which is free to move. The force of repulsion F_1 due to A will tend to make the test-charge move further away from A. In order to move the test-charge from v_1 to v_2 work must be done on it, so that its *potential energy* is greater at v_2 than at v_1. In the same way its potential energy is greater at v_3 than at v_2, and it is greatest at a point as near as possible to the surface of A. The space round A is a region of *electric potential* which

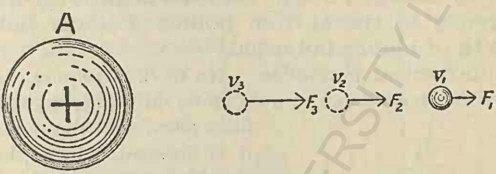


FIG. 101.—The potential is greater at v_3 than at v_1.

gradually diminishes in value as the distance from A increases, and we say that *the electric potential is greater at* v_3 *than at* v_1.

No force will act on the test-charge when it is removed to a great distance from A, consequently the potential at a great distance from A is *zero*.

No electric forces originate from uncharged bodies, hence the region round them (in the absence of any charged bodies) will be one of zero electric potential. An uncharged body has zero potential, and since the earth may be regarded as a huge spherical conductor which is uncharged, it is usual in experimental work to take the potential of the earth as our zero or starting-point for measurement. (In the same way gravitational potential is measured from sea-level.)

If the charge on A is $-$ve, then work must be done in *withdrawing* the positive test-charge from the neighbourhood of A, and most work would be required if the test-charge is almost touching A. Hence the potential is *least* at points *near to* A, and gradually increases as the distance increases, and finally becomes *zero* at a great distance from A. The field round A in this case is said to be one of *Negative Potential.*

From this reasoning we derive the following important rules :—(i.) **A positively-charged body tends to travel**

from a point of higher electric potential to a point of lower electric potential.

(ii.) Since the force acting on the body is in the direction of the lines of force at the point where the body is situated, the movement, if any, will trace out the path of the lines of force.

(iii.) The forces acting on a negatively-charged body are opposite in direction to those acting on a positively-charged body. Hence a negatively-charged body tends to travel from points of lower potential to points of higher potential.

Equipotential Surfaces.—No work is required in order to move our test-charge in a direction at right angles to the lines of force at the point where it is situated. In so doing we should therefore be tracing out a surface of *equal potential*.

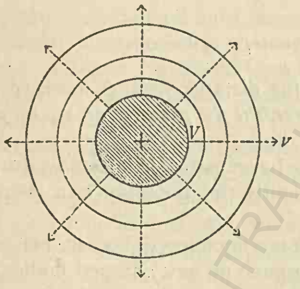


FIG. 102.—Equipotential surfaces round a charged sphere.

In the case of a single charged sphere, since the lines of force radiate outwards from the surface of the sphere, the equipotential surfaces will be spherical surfaces concentric with the sphere. Fig. 102 represents a cross-section through the sphere and its electric field; the thick lines represent the equipotential surfaces.

Fig. 103 represents the equipotential surfaces in the electric field due to two spheres charged to an equal degree with *opposite* electrifications. The potential at *a* is + ve, and as the test-charge moves from *a* towards *b* the potential gradually falls. If the charges on the spheres are equal and of opposite kind, points of zero potential will be mid-way between them (at *c*).

Flow of Electricity.—In the previous sections we have imagined the positive test-charge to be conveyed from point to point on a small insulated sphere surrounded by a non-conducting medium—air. Supposing that the small sphere containing the test-charge is rigidly fixed at some point in an electric field of force, and that a mass of conducting material

(such as a metal) is brought into contact with the small sphere, then the *charge* will leave it if, by so doing, it can move into a region of lower potential. The charge would subsequently be found on that portion of the conductor which is situated in the region of lowest potential.[1]

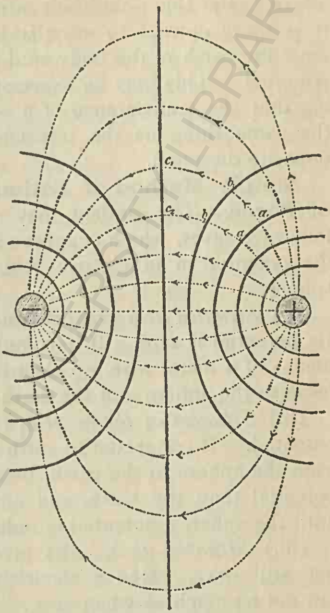


FIG. 103.—Equipotential surfaces due to two oppositely-charged spheres.

Electricity is said to flow in a conductor from points of higher to points of lower potential.—*Difference of potential* and *flow of electricity* are allied to one another as *cause* and *effect*, but the cause will only produce the effect when the medium is a conductor. No current can traverse a perfect insulator although there may be a difference of potential within it; such a medium is only thrown into a condition of *strain*.

If a + ly charged insulated conductor is connected to earth by means of a wire the charge rapidly "flows" along the wire, and the conductor is rapidly discharged. The field of force originally surrounding the conductor has disappeared—in fact, each portion of the charge in its passage along the wire has been accompanied by the lines of force associated with it. The so-called "flow of electricity" may therefore be regarded as a disappearance of lines of force, with the result that the surrounding medium is relieved from its condition of strain.

[1] It will be remembered that, in the case of a field of magnetic force, a magnetic pole cannot *flow* independently of the body in which it exists—the magnetic pole can only be conveyed by the motion of the body itself.

It might be said that the charge from a $-$ly charged sphere would flow along the wire to earth, and pass from a *lower* to a *higher* potential, thus disobeying the conclusion arrived at above. But this would be contrary to the one-fluid theory, and it is more correct to say that electricity flows along the wire *from* the earth *to* the body until the conductor is raised to zero potential. This may be expressed in another manner by saying that the transference of a $-$ve charge in one direction is the same thing as the transference of a $+$ve charge in the opposite direction.

Simple Method of Estimating Potential in a Field of Force.—The student may with advantage consider the following cases, which suggest a simple method of investigating the potential in an electric field. Imagine a small insulated sphere—

(i.) *Situated at a great distance from all charged bodies.*—Its potential is zero. If it is now connected to the earth by means of a metal wire, no electricity will flow along the wire, because the sphere and the earth are both at zero potential.

(ii.) *Situated at the point* a_1 (Fig. 103).—It now has $+$ve potential. If connected to earth by a wire, electricity will flow from the sphere to the earth, because the sphere is at a higher potential than the earth, and electricity will continue to flow until the sphere's potential is reduced to zero.

(iii.) *Situated at* b_1.—Its potential will be less than at a_1, but still $+$ve. Hence electricity will flow along the wire, but not so much as when at a_1.

(iv.) *Situated at* c_1.—Its potential will be zero. Hence no electricity will flow along the wire.

(v.) *Situated to the left of* c_1.—Its potential is $-$ve. Hence electricity will flow from the earth to the sphere.

(vi.) *Situated still farther to the left of* c_1.—Its potential is still more $-$ve. Hence more electricity will flow from the earth to the sphere than in case (v.).

These results may be summed up in the following rules:—

If electricity flows from the sphere to the earth, then the sphere is in a region of $+$ve potential.

If electricity flows from the earth to the sphere, then the sphere is in a region of $-$ve potential.

If no electricity flows, then the sphere is in a region of zero potential.

If the connecting wire is removed in each case without disturbing the sphere, and the sphere itself is then removed to a distance, the following charges would be found on it—(i.) Uncharged, (ii.) and (iii.) Negative, (iv.) Uncharged, (v.) and (vi.) Positive. These results might be experimentally verified by touching the small sphere with the finger instead of with a wire, since the body is also a conductor. We say that the above charges on the small sphere have been acquired by **Electric Induction**, a subject which is fully discussed in the next chapter.

Hydrostatic and Thermal Analogies.—In some text-books the student is initiated into the ideas of electric potential by means of analogies, which, although unsound in principle, are often useful in imparting the main facts of the subject. The following analogies are often adopted :—

(i.) The difference of potential between two charged bodies is compared to the difference of level of water in two cisterns, which are connected by means of a narrow pipe. The difference of level is generally termed the *head* of water. The head of water causes water to flow along the connecting-pipe from the higher to the lower level, and the flow ceases as soon as the level of water is the same in both cisterns. The equality of level in the cisterns is analogous to the equality of potential of two charged conductors which are connected by means of a wire.

(ii.) Heat will pass from a hot body to a cold body placed in contact with one another. The flow of heat depends upon the difference of temperature, and will cease when both bodies are at the same temperature. The difference of temperature is analogous to a difference of potential between two charged conductors.

These analogies particularly fail in not drawing special attention to the field of force between the charged bodies; moreover, the analogies only hold good up to a certain point. The student is consequently recommended not to place too much reliance upon what may, at first sight, be an easy means of understanding the principles of potential.

The Law of Inverse Squares.—**The force which an electrified body exerts on neighbouring bodies (charged or uncharged) varies inversely as the square of the distance.** The student will have observed in his preliminary experiments that the magnitude of electric forces depends upon the distance of the bodies apart. This result would be anticipated if we consider that the forces are due to the lines of force traversing the medium between the two bodies; the more distant the body acted upon, the fewer lines of force from the charged body will it intercept, and therefore the weaker is the force. This suggests a resemblance to the law of Inverse Squares which has been experimentally proved to hold good in the case of Magnetic Forces.

Coulomb has roughly proved, by means of the *Torsion Balance*, that electric forces do obey the law of Inverse Squares. (For a description of the apparatus the student is referred to advanced text-books.[1]) A more satisfactory proof will be given later.

Potential Diagrams of Electric Fields of Force.—A simple method of representing the distribution of potential in an electric field is shown in the following diagrams. The horizontal line represents zero potential, and at various points perpendicular lines are drawn, the lengths of which represent the magnitudes of the potential at the point from which the line is drawn. Positive potential is represented by lines *above* the zero line, and negative potential by lines *below* the zero line.

Fig. 104 (i.) represents the potential diagram for the field round a single +ly charged sphere. ABC is the zero-potential line. A*a*, B*b*, C*c* represent the potentials at the points A, B, and C respectively. The slope of the line *abc* represents the gradual fall of potential as the distance from the sphere increases.

Fig. 104 (ii.) represents the potential diagram for two equally and oppositely charged spheres. A*a* represents the +ve potential at A, and C*c* represents the −ve potential at C. The slope of the line *aa*′B*b*′*c* represents the gradual change from +ve potential at A to zero potential at B, and −ve potential at C. The potential at D is the same as at A,

[1] *Lessons in Electricity and Magnetism*, Prof. S. P. Thompson, pp. 19-23.

because both points are situated on the surface of the same conductor. (This will be proved experimentally in the next chapter.) Beyond D the potential will gradually diminish to zero if no other charged conductors are in the field. At D′

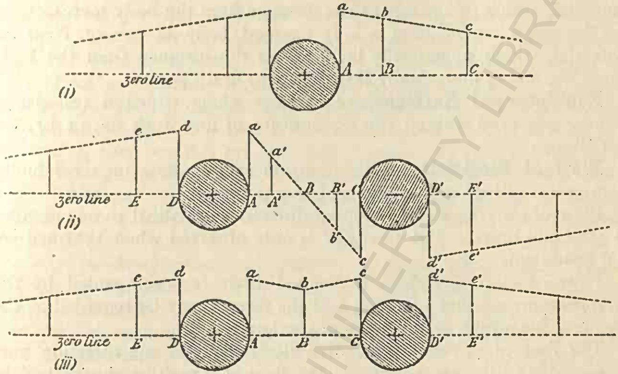


FIG. 104.—Potential diagrams.

the potential is the same as at C; at points more distant than D′ the potential is still −ve, but greater than at D′. The gradual increase of the potential to a zero value is represented by the slope-line *d′e′*.

Fig. 104 (iii.) represents the potential diagram for two equally and similarly charged spheres. N.B.—*In all potential diagrams in this book, the lines indicating fall of potential should strictly be curved, and not straight. The latter form is only adopted for simplicity.*

CHIEF POINTS OF CHAPTER XI

An Electric Field is composed of *electric lines of force* (cf. a magnet field and magnetic lines of force).

The space between two oppositely charged bodies is traversed by lines of force which tend to draw the bodies together. At opposite ends of each line, equivalent quantities of +ve and −ve electrification are found.

The Magnitude of Electric Forces may be regarded as depending upon the number of lines of force called into play.

The direction of the force is arbitrarily chosen as that in which a +ly charged body will tend to move.

Electric Potential.—The potential at any point of an electric field of force is measured by the *potential energy* which a small +ve test-charge would have if placed at that point.

The space surrounding a +ly charged body is one of Positive Potential, which diminishes as the distance from the body increases.

The space surrounding a −ly charged body is one of Negative Potential, which numerically increases as the distance from the body increases, and is numerically less than zero at all points.

Equipotential Surfaces are surfaces along which a test-charge may be conveyed without the expenditure of any work on, or by, the test-charge.

Flow of Electricity.—Electricity is said to flow in a conductor from points of higher to points of lower potential.

Flow of electricity and potential-difference are allied to one another as *effect* and *cause*. But the *effect* is only observed when the medium is a conductor.

Flow of electricity from a charged body is accompanied by the disappearance of lines of force, and the former may be regarded as the phenomenon which is indicative of the latter.

The flow of so-called "negative electricity" in one direction may be regarded as the same thing as the flow of "positive electricity" in the opposite direction.

The Law of Inverse Squares.—*The force which an electrified body exerts on neighbouring bodies varies inversely as the square of the distance.*

Questions on Chapter XI

1. Describe briefly the chief physical properties which are attributed to the lines of force in an electric field.

2. Describe some simple method of observing the direction of the lines of force near to a charged body. Represent, by means of a diagram, the general distribution of the lines of force in the field near to (i.) a charged rod of sealing-wax, (ii.) a metal sphere charged +ly.

3. What is the arbitrary rule which is adopted in order to define the direction in which electric forces may be acting?

4. What is meant by *Electric Potential?* Describe how you would experimentally obtain (i.) a field of Positive Potential, (ii.) a field of Negative Potential.

5. What is an *Equipotential Surface?* Give diagrams showing the general distribution of the equipotential surfaces (i.) round a single charged sphere, (ii.) in the space between two oppositely charged spheres.

6. Two metal spheres of equal size, standing on insulating supports,

are oppositely and equally electrified, one positively, the other negatively. They are then placed near together, but not so near as to produce a spark between them. Describe the general distribution, when so placed, of the charges upon them, and of the electric lines of force in the field between them. (Lond. Matric.)

7. Two equal metallic spheres charged with equal quantities of electricity of the same sign are placed near together, but not in contact. Give a sketch, showing the way in which the electricity is distributed over the spheres. (Lond. Matric. 1897.)

8. Make a potential diagram, indicating the changes of potential along the line joining the centres of two oppositely and equally charged spheres (A and B). If A and B are 20 cms. apart, and points on the line joining their centres are selected 5 cms., 10 cms., and 15 cms. distant from A, describe what changes will take place, in each case, in the electrical condition of a small uncharged sphere which is brought from a distance to the point and then momentarily touched with the finger.

9. An insulated brass ball without charge is hung near a negatively-charged conductor. It is then momentarily connected with the charged conductor. Is its potential altered thereby, and if so, how? It is then momentarily connected with the earth. How does this affect its potential? (1893.)

10. Discuss the analogies between differences of level, temperature, and electrical potential respectively. (1893.)

11. A small insulated uncharged sphere has positive potential if placed near to a positively-charged conductor. How would its potential be modified if it already possessed a slight negative charge? How would the result of connecting it momentarily to the earth then depend upon the distance between the sphere and the conductor?

12. Under what conditions is it possible for a negatively-charged insulated sphere to have (i.) zero potential, (ii.) positive potential?

13. How is the potential of a positively-charged insulated sphere modified by bringing another positively-charged body near to it?

14. What are the two conditions which determine a *flow* of electricity?

15. In what manner can we connect the ideas of "lines of force" and "flow of electricity"?

16. A negatively-charged insulated sphere is discharged by momentarily touching it with the finger. How would you explain this experiment by applying the rule that "electricity tends to flow from points of high potential to points of low potential"?

CHAPTER XII

ELECTROSTATIC INDUCTION

Apparatus required.—Proof plane. Cylinder of wood with rounded ends, and pear-shaped piece of wood—both coated with tinfoil or black-lead. Glass rod, vulcanite, silk, and flannel. Pith-ball and gold-leaf electroscopes. Insulated door-knobs. Insulating stand. Electrophorus. Iron-gauze cylinder. Thin metal plate. Hollow tin vessel. Biot's apparatus. Butterfly net. Small spheres (or tinfoil-coated bottles) on insulating handles.

The Proof Plane.—The *proof plane* is a simple appliance which will be frequently required for experiments on induction; it consists of a disc of thin copper or brass (about 2 cms. diameter) fixed to the end of an insulating handle. A half-penny may be used as a metal disc. A proof plane is represented at the extreme right of Fig. 91.

Introductory Experiment.[1] EXPT. 80.—(i.) Support on an insulating stand a cylinder of wood, with rounded ends, and coated with tinfoil or black-lead. A suitable stand may be made from a rod of unpolished vulcanite, which is fixed vertically in a hole bored in a wooden base.

[1] The student is reminded that the terms "positive" and "negative" continue to be used, not because we assume that there are *two different kinds* of electricity, but because it is generally accepted as the only convenient form of nomenclature. Whenever the term *negative electricity* is used it must be tacitly assumed that this implies *less than the normal amount of electricity*, while *positive electricity* implies *more than the normal amount.*

Hold a glass rod, which has been rubbed with silk, near to one end of the cylinder (Fig. 105). Hold a proof plane with its flat side in contact with the end A of the cylinder. Convey the proof plane to a pith-ball electroscope which is charged − ly, and observe that the proof plane is also charged − ly. While holding the glass rod in the same position as before, touch the distant end of the cylinder with the proof plane, and test the charge on the latter by means of a + ly charged electroscope. Observe that the proof plane is + ly charged. When the proof plane touches the cylinder it becomes part of one and the same conductor, and will therefore acquire a portion of the electrification which may be present at the ends of the cylinder.

The results therefore prove that the cylinder is charged − ly at A and + ly at B. The upper portion of Fig. 105 represents the distribution of the lines of force in the experiment, and the potential diagram through the axis of the cylinder is shown in the lower portion of the same figure. The end A is nearer than B to the glass rod, and is consequently at a higher potential. The cylinder is a conductor, therefore electricity flows from A towards B, and the flow will continue until the potential of the cylinder is uniform. Lines of electric force proceed from the + ve charge on the glass rod to the − ve charge on A; lines of force also proceed from the + ve charge at B towards the walls of the room. *Notice how the lines of force appear to converge towards* A, *and to diverge outwards from* B, *and how this suggests the idea that the cylinder is a*

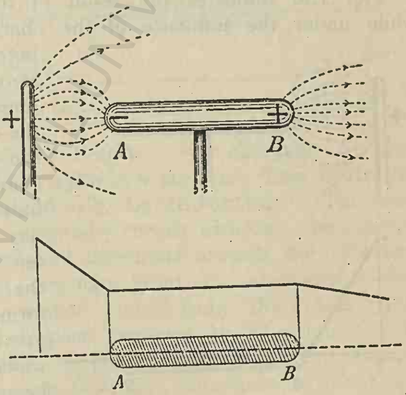


FIG. 105.—Potential diagram of an insulated cylinder charged inductively.

better conductor than the surrounding air for the lines of force. (Compare this with the flow of magnetic lines of force through soft iron.) **We say that the charges on the cylinder are due to induction from the electrified glass rod.**

(ii.) Remove the glass rod to a distance, and again test with the proof plane. No charge is found on the cylinder.

When the glass rod is removed the electric field is conveyed away with it, and no lines of force remain to influence the cylinder. The +ve and −ve charges at A and B have become distributed over the entire cylinder, and have exactly neutralised each other, and must therefore have been present in equal quantity.

(iii.) Again hold the glass rod near to A. Touch the cylinder with the finger, and again test the electrification at A and B. A is charged −ly, and B is uncharged.

Fig. 106 indicates the result of touching the cylinder while under the influence of the charged glass rod. Its potential is reduced to zero, consequently no lines of force pass from the end B to the walls of the room, and the +ve charge formerly distributed over the end B has disappeared. The few lines of force from the glass rod which formerly traversed the greater distance to the walls of the room (or beyond), to terminate there in their equivalent −ve charge, are now able to find this equivalent charge by traversing the less distance to the end A of the earth-connected cylinder; this preference for a shorter path is not a new property, but simply a result of the fundamental tendency to *shorten* shown by all lines of force. We consequently find that rather more lines of force now terminate on the end A than was the case before

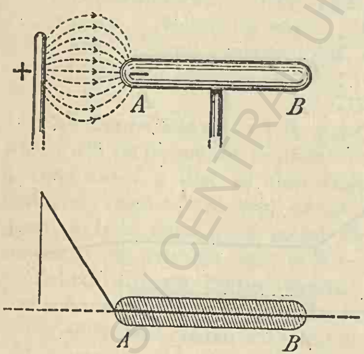


FIG. 106.—After connection with earth.

connecting to earth, resulting in the − ve charge at A being slightly greater *after* being earthed than it was before being earthed.

The fact that the cylinder can be at zero potential while still in a region of + ve potential may be more clearly understood if it is remembered that the cylinder itself has a − ve charge, which would, in the absence of any charged body, give it a − ve potential. The external field, however, tends to give the cylinder a + ve potential. The two effects are equal and opposite, thus giving to the cylinder an apparent zero potential.

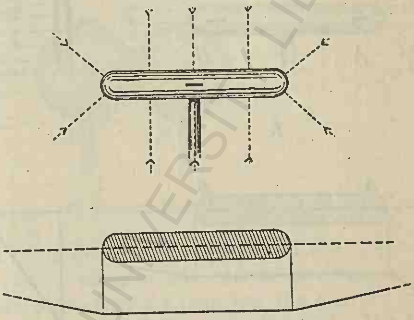


FIG. 107.—After removal of the inducing charge.

(iv.) Remove the glass rod to a distance. Test the charges on the ends A and B. Both are − ly charged. So also are all parts of the cylinder's surface. **The cylinder has been charged − ly by induction.**[1] The lines of force (which essentially coexist with the − ve charge) now proceed from all directions towards the cylinder, and they must originate from an equivalent + ve charge; they cannot come from the glass rod, because this has been removed to a distance, and we shall be able to prove in a subsequent experiment that they come from the boundaries of the room (Fig. 107).

EXPT. 81.—Repeat these experiments, using electrified vulcanite instead of the glass rod. Prove that A is

[1] **Free and Bound Charges.**—These terms are sometimes used in order to distinguish the charge which disappears on touching with the finger from that which still remains on the insulated conductor. Thus, in Expt. 80, the + ve charge on the end B would be termed the *free* charge, and the − ve charge on the end A would be termed the *bound* charge.

+ly electrified, and B −ly electrified, and verify the results shown in Fig. 108.

In Fig. 108 (i.) the point B is in a region of higher potential

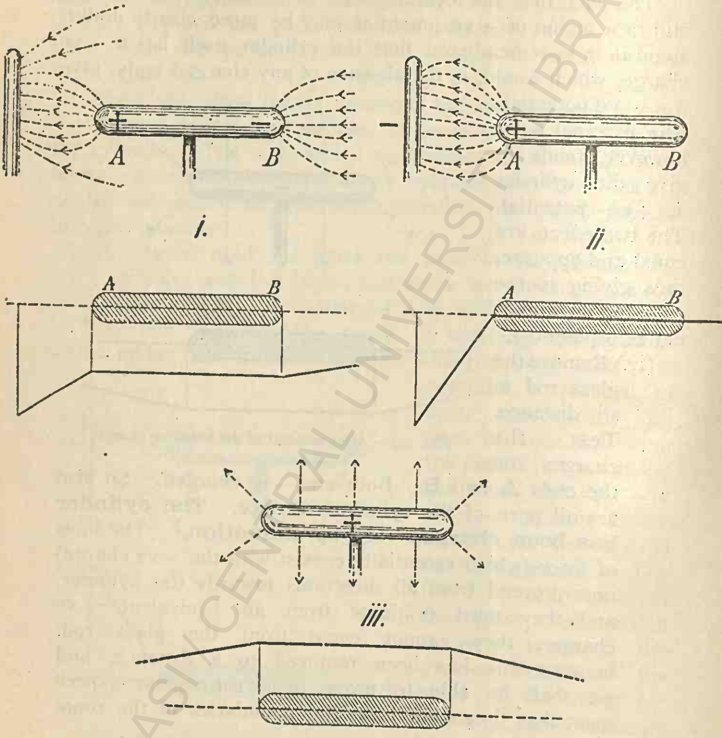


FIG. 108.—Charging an insulated conductor +ly by induction.

than A, consequently electricity flows from B to A. In Fig. 108 (ii.) B has been connected to earth, and electricity has passed up into the cylinder until its potential has been raised to zero; the lines of force entering B have been destroyed. In Fig. 108 (iii.) the sealing-wax has been removed, the +ve

charge formerly at A is now distributed all over the cylinder, which is consequently *charged* + *ly by induction.*

Simple Verification of these Results. EXPT. 82.—Instead of the cylinder use two small metal spheres (brass door-knobs are convenient), each supported independently on a vertical insulating support. Place them

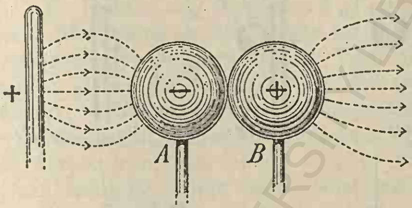


FIG. 109.—To illustrate Expt. 82.

in contact, and bring an electrified glass rod near to one of them (Fig. 109). Keeping the rod in position, now remove the more distant sphere, and test the charges on both spheres. A is − ly and B is + ly charged. While in contact they act as one conductor, and the charge on the glass rod acts upon them as if such were the case.

Attraction of Uncharged Bodies due to Induction.—If, in Expt. 80, the cylinder had been free to rotate round its point of support, and if the charged glass rod had been held to the right or left of the end A, then the lines of force would have caused the cylinder to approach the rod; for the same reason, if the rod had been held above (or below) the end A, then the latter would tend to rise (or fall).

Experimental results similar to this have already been obtained with a long wooden lath (Expt. 66), and by using a proof plane it is easy to verify the *induced charges* at the ends of the lath.

The attraction of light objects (Expt. 65) is due to the same effect. Each fragment is acted upon *inductively* before attraction takes place. But if the fragments are lying on the table they are earth-connected, so that the field of force is analogous to that of Expt. 80 *after the cylinder has been touched.*

Each stage of the action of a charged glass rod on a pith-

ball electroscope is represented in Fig. 110. (i.) shows attraction of the pith-ball. (ii.) shows the pith-ball drawn up into contact with the rod, thus destroying the lines of force between the rod and the near side of the ball. The lines of force from

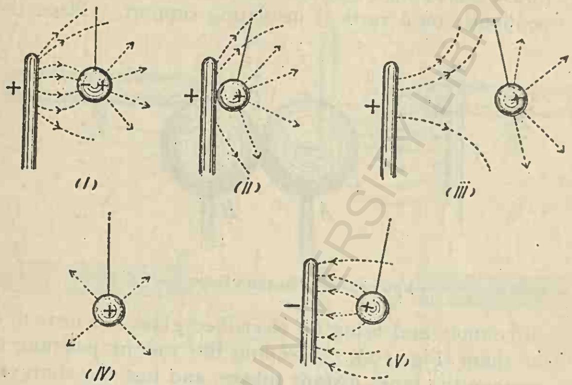


FIG. 110.—Stages in the action of a charged rod on a pith-ball electroscope.

the distant side of the ball now tend to pull it away from the rod, with the result shown in (iii.). This is a simple case of repulsion between similarly charged bodies. (iv.) represents the ball charged +ly after the rod has been removed to a distance. (v.) represents the effect produced by bringing a −ly charged rod near to the +ly charged pith-ball.

Theory of the Gold-Leaf Electroscope.—The theory of Expts. 80 and 81 is directly applicable to the gold-leaf electroscope (for description of the instrument see p. 132). Instead of the insulated cylinder we have an insulated conductor, with a flat metal disc at its upper end, and a pair of metal leaves at its lower end. Fig. 111 represents the electroscope under different electrical conditions. AB and CD represent the strips of tinfoil on the inner surface of the glass, and BD is the disc of foil on the base-board. ABCD is earth-connected through the table on which the instrument stands, and therefore has a *constant zero potential*.

Fig. 111 also includes a potential diagram for each case;

the diagrams indicate the changes of potential along a line coinciding with the axis of the electroscope. The vertical dotted line is taken as the line of zero potential. Positive potentials are represented by horizontal lines drawn to the *right* of the zero line, and negative potentials by lines drawn to the left. The thick continuous line represents the changes in potential along the line of the electroscope's axis.

EXPT. 83.—(i.) Hold a $-$ly charged rod of vulcanite over the disc. The leaves are at a higher potential than the disc, consequently electricity passes from the leaves to the disc, giving the former a $-$ve and the latter a $+$ve charge. The charge on the leaves induces a $+$ve charge on the tinfoil. Lines of force (see Fig. 111, i.) proceed across from each tinfoil strip to the nearest metal leaf, resulting in the leaves being pulled apart. The same number of lines of force also pass from the disc to the vulcanite. The degree of divergence will depend upon the number of lines of force passing between the leaves and the tinfoil.

(ii.) Hold the vulcanite still in same position, and touch the disc with the finger. The potential of the leaves is raised to zero, the lines of force between the tinfoil and the leaves disappear, and the leaves collapse (Fig. 111, ii.).

(iii.) Remove the vulcanite to a distance. The $+$ve charge distributes itself uniformly over the conductor, a portion going into the leaves and inducing a $-$ve charge on the tinfoil. The lines of force thus brought into play cause the leaves to diverge (Fig. 111, iii.). *The electroscope has been charged $+$ly by induction.*

(iv.) Hold a $+$ly charged glass rod over the disc. The potential of the disc is raised above that of the leaves. More electricity enters the leaves, and the increased number of lines of force causes the leaves to diverge more (Fig. 111, iv.).

(v.) Hold a $-$ly charged rod of vulcanite over the disc. The potential of the disc is lower than that of the leaves. Electricity passes from the leaves to the disc, thus diminishing the number of lines of force between the leaves and the tinfoil (Fig. 111, v.).

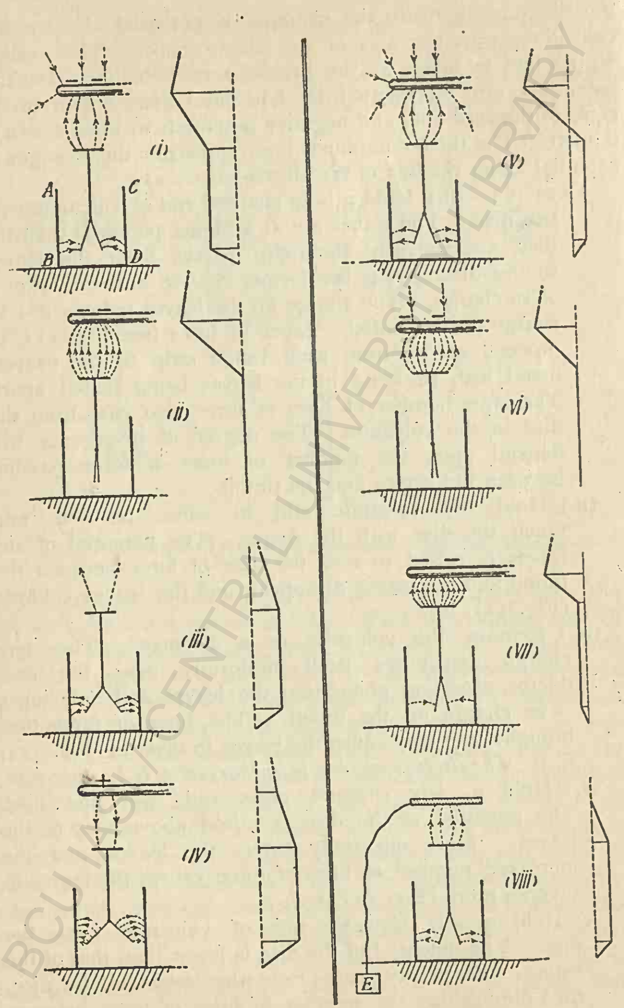


FIG. 111.—A gold-leaf electroscope under various electrical conditions.

(vi.) Hold the vulcanite nearer to the disc. The potential of the disc is still further diminished, more electricity passes from the leaves to the disc, and the divergence of the leaves is diminished. If the potential is reduced to zero the leaves will have no divergence (Fig. 111, vi.).

(vii.) Hold the vulcanite still nearer to the disc. The potential of the disc is now negative, and the leaves will diverge with −ve electricity (Fig. 111, vii.).

(viii.) Remove the vulcanite to a distance, and hold the hand, or some other earth-connected conductor, over the disc. The +ve charge on the disc now induces a −ve charge on the under side of the hand, resulting in some (or all) of the lines of force being transferred from the leaves to the disc, and so reducing the divergence of the leaves. The nearer the hand is to the disc the greater is the reduction in the divergence of the leaves (Fig. 111, viii.). The same result may be expressed by saying that the induced −ve charge on the hand creates a region of −ve potential round the disc, and consequently lowers the potential of the instrument.

(ix.) Repeat (i.) and (ii.), but use a +ly charged glass rod instead of the vulcanite. The electroscope will now be charged −ly. A +ly charged body held over the disc will now *diminish* the divergence, and a −ly charged body will *increase* the divergence. An earth-connected conductor held over the disc will *diminish* the divergence (the same as when the instrument is +ly charged).

(x.) Place the uncharged electroscope on an insulating stand.[1] Connect the disc to the tinfoil base by means

[1] **Insulating Stands.**—A simple form of insulating stand is frequently required in electrostatic experiments. Flat slabs of white paraffin-wax serve the purpose admirably. The wax may be cast by melting it in a baking-tin of the required size, and allowing it to cool; when cold the tin is placed in hot water for a few moments, till the outer layer of wax is melted, and then inverted, so as to remove the slab of wax. The wax should be originally melted by standing the tin in a vessel of water heated from below, since the wax loses its insulating power considerably if heated much above the temperature of boiling water.

If a taller insulating stand is required, a suitable form may be made in the following manner:—Fix a vulcanite rod vertically into a wooden

of a thin wire. Hold a charged body near to the instrument, and observe that the leaves do not diverge. The leaves and the tinfoil are at the same potential, and therefore no lines of force pass between them to cause a divergence.

Remove the thin wire, and observe that a charged body near to the instrument will cause a divergence of the leaves. If the charged body is an electrified glass rod, the potential of the leaves and of the tinfoil will be raised, but not to the same degree; hence there will be a potential difference causing a divergence of the leaves.

Touch the tinfoil with the finger, so as to reduce its potential to zero. The potential difference is now greater, and this is shown by the increased divergence.

From these results we see that the divergence of the leaves depends upon the potential difference between the leaves and the earth-connected tinfoil; if the instrument is + ly charged, a *rise* in the potential of the leaves will produce an *increased* divergence; a *fall* in potential will produce a *reduced* divergence. The electroscope may therefore be used as a means of detecting any changes in potential.

This principle may also be applied in order to determine the kind of electrification on a body which is held over the disc, for if the body is + ly charged the potential of the electroscope is raised, and if the body is – ly charged the potential of the electroscope is lowered. The rules to observe will be as follows:—

Electroscope charged + ly.	Increased divergence *implies* + ve charge. Diminished divergence *implies* – ve charge (*or* an earth-connected conductor).
Electroscope charged – ly.	Increased divergence *implies* – ve charge. Diminished divergence *implies* + ve charge (*or* an earth-connected conductor).

base. Bore a hole in a wide cork so as to fit tightly on the upper end of the rod. Fix a slab of wax horizontally on the top of the cork. The insulation is improved if the rod is unpolished.

From these rules it will be seen that an *increased divergence* is the only sure test of electrification.

The Electrophorus.—This is a convenient appliance for obtaining larger charges of electricity than can be obtained from electrified glass rods or vulcanite rods. It was devised by Volta in 1775. The principle of its action is identical with that described in Expt. 81, in which experiment the cylinder and the vulcanite rod are replaced by a flat metal disc and a circular slab of sealing-wax (or shellac).

FIG. 112.—An electrophorus.

A simple form of electrophorus may be made by filling the inverted lid of a coffee-tin (8-10 cms. diameter) with melted sealing-wax. Cut a circular disc of brass or copper of slightly less diameter than the tin-lid, and fasten the disc at right angles to the end of a rod of vulcanite, which serves as an insulating handle; the portion of the brass surface to which the handle is attached should be previously scratched or roughened, to enable the vulcanite to cling more firmly.

EXPT. 84.—Charge the sealing-wax $-$ly by rubbing with fur or flannel. Place the metal disc resting on the top of the sealing-wax. Touch the disc. Raise the disc away from the sealing-wax. Test the charge on the disc by holding it over the disc of a $+$ly charged gold-leaf electroscope; an increased divergence shows that the electrophorus disc is $+$ly charged. Bring the finger near to the disc; when sufficiently near, a small spark is seen to pass from the disc to the hand. Completely discharge the disc by touching it with the hand. Again place it on the sealing-wax, and repeat the experiment. The disc may be charged many times without it being necessary to re-charge the sealing-wax.

It might appear that when the disc, lying on the wax, is touched that the sealing-wax would be immediately discharged. The reason for this not being so is that the disc is really only

touching the sealing-wax at three or four points, since neither of the surfaces in contact are perfectly true planes; these points may be discharged, but other portions of the surface will retain their charge, because they are separated from the points of contact by the insulating sealing-wax. Fig. 113 represents the various stages in the experiment. In Fig. 113 (i.) and (ii.) the disc is represented much farther away from

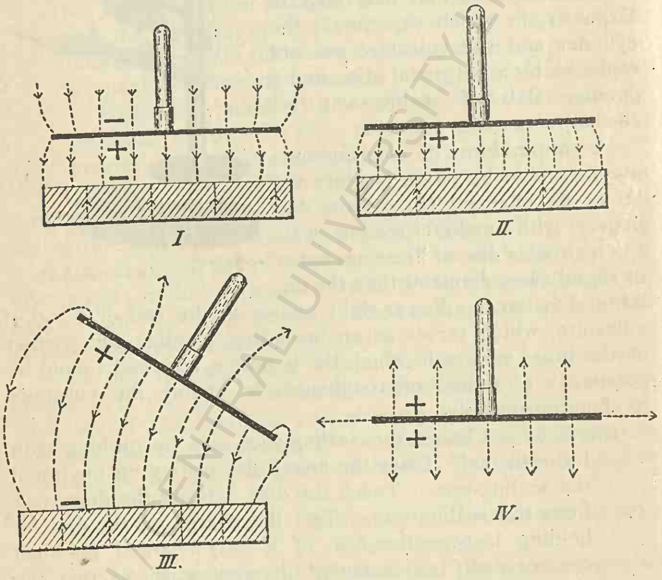


FIG. 113.—The principle of the electrophorus.

the wax than really is the case, so as to show clearly the lines of force between the disc and the wax.

When the disc is charged and brought near to an earth-connected conductor, a spark passes which is accompanied by sound, light, and some heat. It is evidently a source of energy, which is not the case before the disc is charged. This energy only appears when the disc has been raised, and the work done on the disc in stretching the lines of force

which connect it to the wax reappears in the energy of the spark which the disc is capable of giving off when an earth-connected conductor approaches it.

Electrical Screening.—So far we have only investigated the paths of the lines of force in the immediate neighbourhood of the apparatus which is being experimented with. When a +ly charged body is in the centre of an otherwise empty room, do the lines of force terminate at the walls, ceiling, and floor of the room? or, do they proceed onwards and outwards? We now know that the latter would be true if the boundaries of the room are *not* earth-connected conductors; but if the reverse is the case, then they will become charged −ly by induction, they will remain at zero potential, and the lines of force will terminate on the surfaces which carry the induced −ve charge.

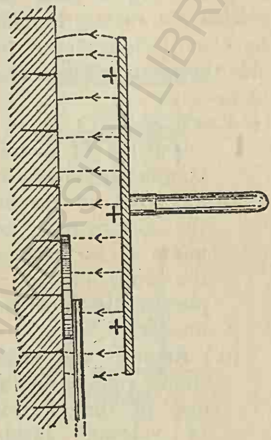


FIG. 114.—To illustrate Expt. 85.

EXPT. 85.—(i.) Hold the charged electrophorus disc 3 or 4 cms. away from the wall of the room (Fig. 114). Touch with a proof plane the surface of the wall which is within the shadow of the disc. Bring the proof plane over the disc of a −ly charged electroscope. The proof plane is charged −ly. Remove the electrophorus disc, and again test the same portion of the wall. The induced −ve charge has disappeared. Hence the walls of the room must be of conducting material.

(ii.) Repeat the experiment, holding the disc just above the table. The same results are obtained.

All the boundaries of the room must be of conducting material. The same may be said of the entire building. Hence we may regard the room as an earth-connected con-

ductor, and always at zero potential. Whatever experiments may be in progress, the lines of force will be restricted to the space within the room, and it will be impossible to detect any electrical forces beyond the boundaries. *The walls, etc., of the room may be said to serve as an electrical screen, protecting the outer region from all electrical forces which may exist within the room.* Similarly, the space within the room will be electrically screened from all forces which may exist outside the room. These results may be verified in the following manner:—

EXPT. 86.—(i.) Make a cylindrical jacket of iron gauze, consisting of gauze sides and top, large enough to completely cover the electroscope without touching any part of the instrument. Place the jacket over the electroscope, and standing on the table; the gauze is earth-connected, and therefore analogous to the walls of the room. Hold the charged electrophorus disc near to the gauze. The electroscope is unaffected.

(ii.) Remove the jacket, invert it, and place it on a stand (non-insulating) as near as possible to the disc of the electroscope. Hold an electrified rod of vulcanite inside the jacket (without touching the gauze). Notice that the electroscope is again unaffected.

(iii.) Hold the vulcanite just over the disc of the electroscope. Observe the divergence. Now place a large sheet of metal, earth-connected by holding it in the hand, between the rod and the disc (*and not touching either*). Observe the collapse of the leaves. *The metal plate is screening the electroscope* (Fig. 115, i.).

(iv.) Replace the earth-connected metal sheet by an insulated sheet. The electroscope is no longer screened (Fig. 115, ii.).

We have already learned that the easiest method of completely discharging a charged body is to pass it through a flame. If the body is a conductor, it is not even necessary to bring the flame into contact with it, the discharge taking place when the flame is still several cms. distant. The con-

ductor will, however, retain its charge if it is electrically screened from the flame by the method shown in Fig. 115 (i.).

(v.) Hold a burning taper or match near to the disc of a charged electroscope. Notice how rapidly the instrument is discharged. Re-charge the electroscope, and hold an earth-connected metal plate between the disc and the flame; notice that the instrument is not being

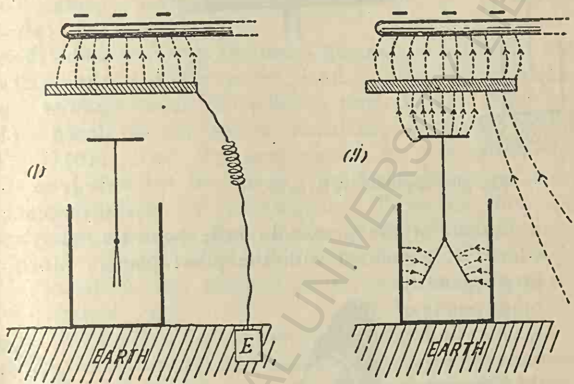


FIG. 115.—An electroscope is screened by an earth-connected metal disc, but not by an insulated disc.

discharged as long as it is screened, but that the discharge takes place as soon as the screen is removed.

Potential the same at all Points of a Conductor.—That the potential is the same at all points of a conductor may be verified by deduction from the fundamental facts of statical electricity. When two points on the surface of a conductor are at different potentials, electricity will continue to pass between them until they are at the same potential. Hence, in an electric field which is not changing, all points of a conductor must be at the same potential. The same conclusion may be arrived at experimentally in the following manner:—

EXPT. 87.—Charge the insulated cylinder (as used in Expt. 80) by means of the electrophorus. Connect the disc of a proof plane to the disc of a gold-leaf

electroscope by means of a thin copper wire. (It is convenient to bore two small holes through the discs.) Holding the proof plane by its insulating handle, bring it into contact with the cylinder, and observe the divergence produced (Fig. 116). The degree of divergence is a measure of the potential of the point on the cylinder which is in contact with the proof plane. Move the proof plane to other points of the cylinder, and notice that the divergence remains unaltered.

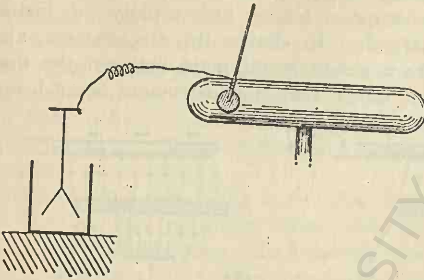


FIG. 116.—To illustrate Expt. 87.

Seat of the Charge on a Conductor. — Having investigated the field of force outside charged bodies, we have now to consider the space within a charged body, and to find if lines of force are present inside as well as outside, or if the charge is uniformly distributed through the substance of the charged body.

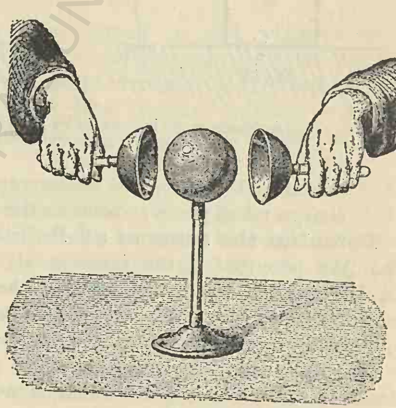


FIG. 117.—Biot's apparatus.

In the case of a solid conductor, we know that the potential at all points must be the same; between these points there

cannot therefore be any electrical lines of force. Hence the lines of force in the external field must terminate *on the surface* of the conductor, and the electrical charge must consequently be restricted to the surface. This has been experimentally verified by Biot, with a simple appliance which is still termed Biot's apparatus (Fig. 117). This consists of an insulated brass sphere over which can be fitted two thin hemispherical brass shells, each supported on an insulating handle.

EXPT. 88.—Charge the metal sphere, and verify the charge by means of the proof plane. Place the hemispheres carefully round the sphere; now, *without touching the sphere* (so far as is practically possible), withdraw them. Test the hemispheres for electrical charges, and also test the sphere; the hemispheres are charged, the sphere is uncharged. Evidently the charge has passed to the outside of the hemispheres, and the removal of the thin outer layer of the combined apparatus has resulted in the complete removal of the charge.

In the case of a *hollow* conductor we can experiment more readily, since it is easy to introduce a proof plane within the conductor, and remove a portion of any charge which may be present.

EXPT. 89.—Place a coffee-tin (or calorimeter) on an insulating stand (p. 163). Charge the tin by means of the electrophorus. Touch the outside of the tin with a proof plane, and verify the charge with a gold-leaf electroscope. Discharge the proof plane, and with it touch the inside of the tin; carefully remove the proof plane without touching the edge or outer surface of the tin. Test it by means of the electroscope; it is uncharged. **Hence there is no charge inside a conductor (solid or hollow).** If the tin could be turned inside out, would the outer surface be still charged although now *inside* the tin? or, would the charge leave it and pass to the surface which is now *outside?* These questions may be experimentally answered by using a cotton net, supported on an insulated handle, and which can be turned inside out by means of a long silk thread

attached to the end of the net (Fig. 118). This is frequently known as *Faraday's Butterfly Net.*

EXPT. 90.—Charge the net by means of the electrophorus. Test for the charge outside and inside by means of a proof plane. The charge is entirely on the outside. Now turn the net inside out, taking care not to touch the cotton net with the hand. Again test the inner and

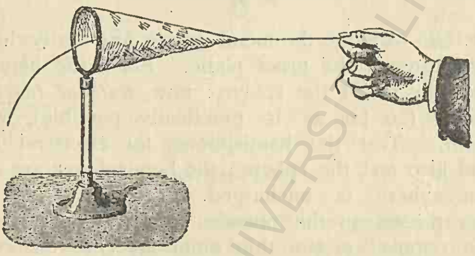


FIG. 118.—Faraday's butterfly net.

outer surfaces. The charge is again found on the outside only. This proves that it is a fundamental property of an electric charge to distribute itself on the outer surface only of a conducting body.

Induced Charges inside a Hollow Conductor.—In the section on "Electrical Screening" we found that the lines of force proceeding from a charged body terminate on the inner surfaces of any earth-connected conductor which may surround it. When the walls of the room make such an earth-connected conductor, we already know that the *induced* charge is present on the walls. This can be verified on a small scale by the following experiment.

EXPT. 91.—Place a small can on the table. Introduce an insulated sphere,[1] which is charged +ly, well inside the can, taking care that the sphere does not touch the can. Touch the inside of the can with a proof plane, and withdraw it, being careful not to touch the sphere or the

[1] Instead of the sphere, a convenient carrier may be made by covering the outside of a 2 oz. glass bottle with tinfoil, and fastening a rod of vulcanite to the cork to serve as an insulating handle.

edge of the can. Test the charge on the proof plane by means of an electroscope. The inside of the can has an induced − ve charge.

We have not yet determined whether the induced charge is equal to the inducing charge. Theoretically they should be equal, since we know that the number of lines of force which terminate on the walls of the room must be equal to the

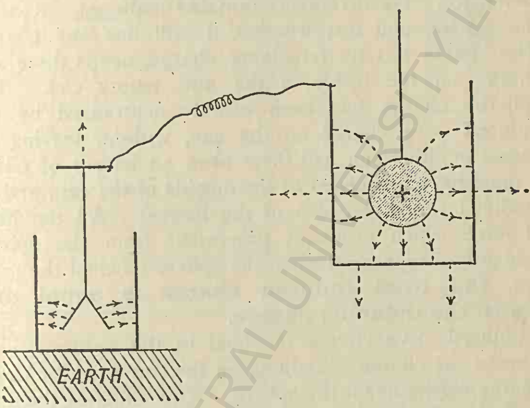


FIG. 119.—Faraday's ice-pail experiment.

number which originate from the charged body within the room, providing that no other charged bodies are present. To verify this by experiment we can imitate the required conditions by means of *Faraday's Ice-pail Experiment* (so called because Faraday first performed the experiment, and used an ice-pail as a hollow conductor).

EXPT. 92.—Place a small can on an insulating stand, and connect the can to the disc of an electroscope. Introduce an insulated sphere (or foil-covered bottle), which is charged + ly, well inside the can, taking care not to touch the sides of the can (Fig. 119). If the can is sufficiently deep, all the lines of force from the charged sphere are now intercepted by the sides of

the can, on the inside of which an induced −ve charge is found. The induced +ve charge is distributed partly over the outer surface of the can and partly over the electroscope, from both of which there are lines of force proceeding to any neighbouring earth-connected conductors. Observe the divergence of the leaves. Allow the sphere to touch the inside of the can, thus making it a portion of the inside of the charged conductor. The divergence remains unaltered. Remove the sphere, and test whether it still has any charge. The sphere has no remaining charge, nor is there any charge on the inside of the now empty can. The sphere's charge has been exactly neutralised by the induced −ve charge on the can, without leaving an excess of either (for had there been an excess of either it must have proceeded to the outside of the can, and so modified the divergence of the leaves). All the lines of force which originally proceeded from the sphere evidently disappeared when the sphere touched the can.

Hence, **the total induced charge is equal and opposite to the inducing charge.**

The induced +ve charge is equal to the induced −ve charge, hence the charge remaining on the can must be equal to the charge originally on the sphere. This explains the only method which is known for completely transferring the charge from one insulated conductor to another. The conductor which is intended to receive the charge must be hollow and of sufficient size to allow the charged conductor to be placed inside it. If the conductors only touch one another on the outside, then the charge will be *shared* between them, and will not be found on one conductor only.

EXPT. 93.—Using the same apparatus as in Expt. 92, touch the outside of the tin with the charged sphere. Observe the divergence of the leaves. Lines of force proceed from both the sphere and the can. Test the charge still remaining on the sphere by bringing it near to the disc of another electroscope which is charged +ly. Now touch the inside of the can with the sphere. Notice the increased divergence, and verify that the sphere is now completely discharged (Fig. 120).

The Potential inside a charged hollow conductor is uniform. We have already proved that there is no charge on the inside of a charged hollow conductor, and therefore no lines of force are present within the conductor. As a result of

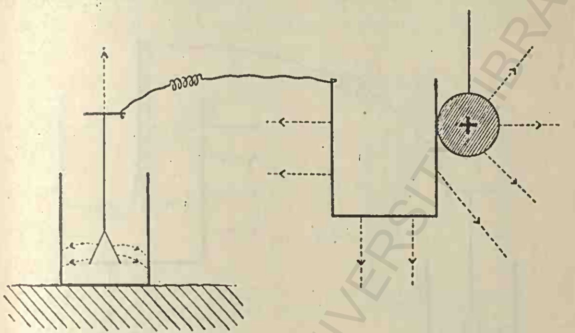


FIG. 120.—To illustrate Expt. 93.

this, no work will be done on a test-charge when carried from point to point within the conductor; in other words (p. 146), the potential must be the same at all points.

EXPT. 94.—Place the gauze jacket (see Expt. 86) on an insulating stand, and place a gold-leaf electroscope inside the jacket. Charge the jacket by means of an electrophorus. The leaves do not diverge, showing that the electroscope is in a region of uniform potential.

Although the potential inside the conductor is uniform, it does not follow that it is *zero*. If the conductor is charged +ly, we should anticipate that any point within the conductor will have +ve potential, since a +ve charge is in the near neighbourhood.

EXPT. 95.—Place a metal can on an insulating stand, and charge it +ly. Connect one end of a long thin wire to the disc of an electroscope, and wrap the other end round the end of a rod of vulcanite, so that the wire may be held inside the can and yet be insulated. Place the electroscope at a sufficient distance to prevent the charge on the can from acting inductively upon the

electroscope. Hold the wire in the centre of the can, and notice the divergence of the leaves (Fig. 121). The potential of the free end of the wire is evidently not *zero*. Move the wire into various positions inside the vessel, and notice that the divergence remains the same.

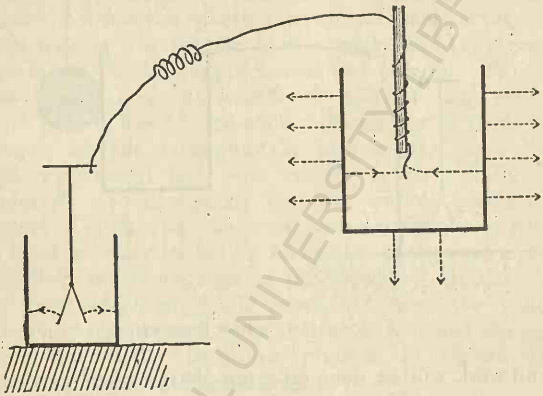


FIG. 121.—To illustrate Expt. 95.

Therefore the potential must be the same at all points. Without withdrawing the wire carefully disconnect it from the electroscope, using a rod of vulcanite or other insulating material for the purpose. Test the charge now present in the electroscope. If it is + ve it proves that the free end of the wire was in a region of + ve potential.

In carrying out this experiment the student may accidentally touch the sides of the can with the wire, which would be accompanied by an increase in the divergence of the leaves. This might, at first sight, appear contrary to the principle that the potential is the same at all points.

EXPT. 96.—Repeat Expt. 95, and allow the wire to touch the inside of the can.

The reason for the increased divergence is that the electroscope now ceases to be merely a measurer of potential, but forms part of one large conductor, consisting of the can and

the electroscope; and the charge, which was formerly restricted to the outer surface of the can, now distributes itself over both can and electroscope. The lines of force will, in fact, tend to accumulate on the leaves more than on the can, because the path between the leaves and the earth-connected strips of tinfoil on the electroscope is far shorter than the path between the

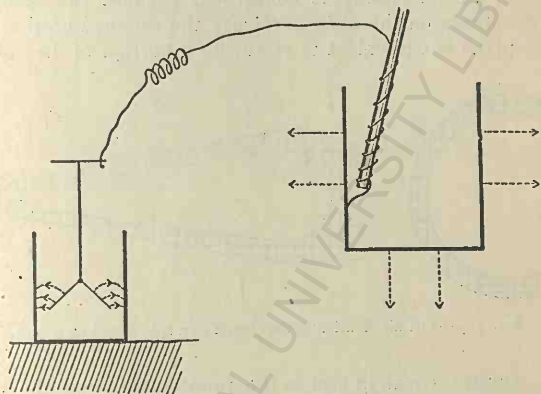


FIG. 122.—To illustrate Expt. 96.

vessel and the walls of the room (Fig. 122). If this is a correct explanation, then the increased divergence should be far less if the strips of tinfoil are insulated from the earth.

EXPT. 97.—Place the electroscope on an insulating stand, and repeat Expt. 96. Observe the divergence when the wire touches the can. Now touch the tinfoil strips with the finger, still keeping the wire and can in contact, and observe the increased divergence.

Distribution of a Charge on the Surface of a Conductor.—Although the potential of a conductor is the same at all points, it does not necessarily follow that the charge is uniformly distributed over the surface. Does the distribution depend in any way upon the shape of the conductor?

EXPT. 98.—(i.) Charge a large insulated sphere. Touch the surface with the flat side of a proof plane, and bring the proof plane into contact with the disc of an un-

charged electroscope. Notice the degree of divergence. Discharge the proof plane and electroscope. Test other portions of the sphere's surface in the same way. The divergence is the same in each case. When the proof plane is touching the surface of the sphere it becomes a portion of the sphere's surface (so far as the distribution of the electricity is concerned, because the charge is entirely on the *outer* surface); the removal of the proof plane is equivalent to removing a portion of the sphere's

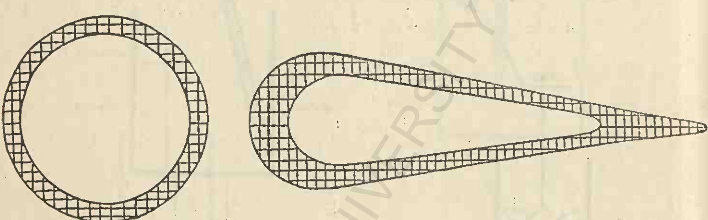


FIG. 123.—The distribution of the charge on a sphere and on a cone.

surface equal in size to the proof plane, and the divergence of the leaves therefore measures the quantity of electricity on such a portion.

The distribution of electricity on the surface of a sphere is uniform (Fig. 123).

(ii.) Repeat this experiment with a large insulated pear-shaped conductor. The greatest divergence is obtained when the proof plane has touched the small end, and the least divergence when the proof plane has touched the straight sides (Fig. 123).

(iii.) Repeat the experiment, using a charged hollow can. More electricity is found on the edges than on the sides.

(iv.) Repeat the experiment, using a charged flat metal disc. More electricity is obtained from the edge than from the sides.

The quantity of electricity on each square centimetre of the surface of a conductor is not necessarily the same. (This quantity is usually termed the **Density** of the charge.)

Hence, *although the potential of a charged conductor is*

uniform, the density is not necessarily so, but depends upon the shape of the conductor.

This result may be difficult to understand, but the consideration of one or two simple cases will show that it is in perfect agreement with what we have already learnt about Statical Electricity. Thus, consider the insulated pear-shaped conductor placed in the field of force due to an insulated charged sphere (Fig. 124, i.). The number of lines of force which

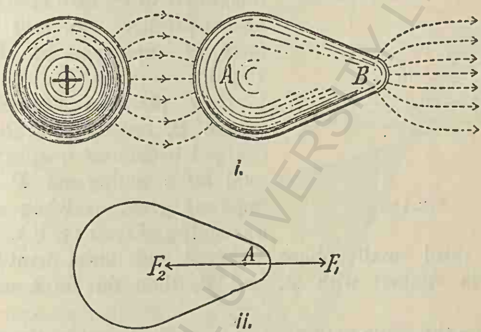


FIG. 124.—The potential of the cone AB is uniform, but the density is greater at B than at A.

leave the pointed end B must be equal to the number which enter the blunt end A; and, since the area of the end B is smaller than the area of the end A, the lines of force must necessarily be more crowded at B than at A. (This is quite analogous to the distribution of magnetic lines of force at the ends of a piece of soft iron, of similar shape to the conductor AB, when placed in a magnetic field.)

Again, the potential at all points inside the conductor must be the same (Fig. 124, ii.). Imagine a small test-charge at A, near to the apex of the charged conductor. The charge on all points of the conductor to the left of A will exert a force F_1 upon the test-charge. Since the potential is uniform, then the charge on all points of the conductor to the right of A must exert an equal and opposite force F_2; for this to be possible, the density of the charge on the point must be considerably greater than that on other portions of the conductor's surface.

The Law of Inverse Squares. Proposition I.—*The force exerted by a charged conductor on a neighbouring test-charge is directly proportional to the quantity of electricity on the conductor.*

Let A be a small sphere, charged with a small quantity of electricity, and let us call this our *unit of quantity.* At a short distance place a test-charge at P, and imagine it to be also charged with *unit* quantity. A will exert a force of repulsion on P (Fig. 125, i.).

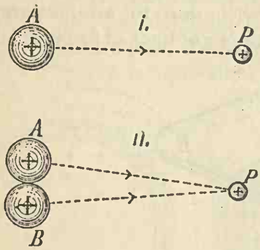


FIG. 125.

Now place a second small sphere B, touching A, and also charged with *unit* quantity. The total force acting on P is now *twice* as great as when A alone was acting (Fig. 125, ii.).

If a third small sphere, charged with unit quantity, were placed in contact with A and B, then the force would be *trebled.*

Hence the force acting on P is proportional to the quantity of electricity at AB.

Proposition II.—*The force exerted by a charged conductor on a neighbouring charged conductor is inversely proportional to the square of the distance.*

Let OAB (Fig. 126) represent a cone with circular base, and Oab a smaller cone formed by making a horizontal section through the larger cone. The radius AP of the base of the cone is proportional to the height OP of the cone (see Fig. 34), or

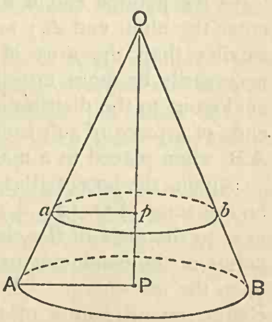


FIG. 126.

$$\frac{AP}{ap} = \frac{OP}{Op}.$$

The *area* of the circular base is proportional to the square of its radius, hence

$$\frac{\text{area AB}}{\text{area } ab}=\frac{(\text{AP})^2}{(ap)^2}=\frac{(\text{OP})^2}{(\text{O}p)^2};$$

or, *the area of the base is proportional to the square of its distance from the apex.*

Apply this result to a point P (Fig. 127) inside a hollow charged sphere. Imagine the sphere divided into a large number of cones, each having P as apex, by drawing straight lines across the sphere through P. Consider one pair of cones as shown in Fig. 127. The charge on the sphere's surface is uniform, hence the quantity of electricity on the areas S and s will be proportional to the size of the areas (which are at distances D and d from the point P), or

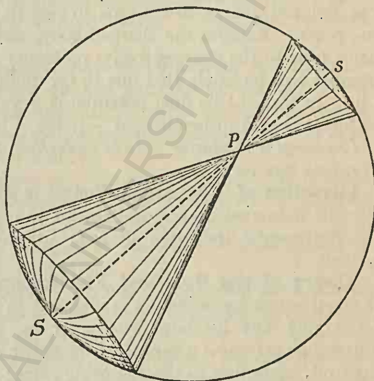


FIG. 127.

$$\frac{Q}{q}=\frac{S}{s}=\frac{D^2}{d^2}.$$

But the forces acting at P exerted by these charges must be equal and opposite, since the potential is the same at all points inside the sphere. Hence the effect of *distance* must neutralise that of *quantity*. If the quantity varies *directly* as the square of the distance, then the force must vary *inversely* as the square of the distance.

CHIEF POINTS OF CHAPTER XII

Fundamental Principle of Electrostatic Induction.—When an insulated conductor is placed near to a charged body, its opposite sides are found to be oppositely charged, and the "sign" of the charge on the near side is opposite to that on the charged body. The opposite sides of the conductor are said to have *induced* charges.

Such a conductor intercepts lines of force passing to or from the charged body. Where lines of force enter the conductor a −ve charge is found, and where lines of force leave the conductor a +ve charge is found.

Charging an Insulated Conductor by Induction.—(i.) An insulated uncharged conductor near to a +ly charged body has +ve potential; (ii.) if near to a −ly charged body its potential is −ve. When momentarily put to earth the potential of the conductor will be *lowered* to zero in case (i.), and *raised* to zero in case (ii.). In case (i.) the +ve induced charge disappears, in case (ii.) the −ve induced charge disappears. Remove the charged body, and the potential of the conductor (due to the charged body) no longer has effect—the conductor's potential will be solely that due to the induced charge still remaining in it. In case (i.) its final potential is −ve, in case (ii.) +ve, and the conductor is said to be charged −ly (or +ly) by induction.

To charge a conductor −ly by induction, the inducing charge must be +ve, and vice versa.

Attraction of Uncharged Bodies is due to Induction.—Just as magnetic induction precedes attraction in magnetic phenomena, so also does electrostatic induction precede attraction in electric phenomena (p. 160).

Theory of the Gold-leaf Electroscope.—The mode of charging the electroscope by induction is identical in principle with the process of charging any insulated conductor by induction. The gold-leaf electroscope serves as a means of detecting a charge in any body held near to it, according to the following rules:—

Electroscope charged +ly	*Increased divergence implies* +ve *charge.* *Diminished divergence implies* −ve *charge* (*or an earth-connected conductor*).
Electroscope charged −ly	*Increased divergence implies* −ve *charge.* *Diminished divergence implies* +ve *charge* (*or an earth-connected conductor*).

The Electrophorus is a simple appliance for repeatedly charging an insulated metal plate by induction. The plate is placed on an electrified disc of sealing-wax or ebonite, and momentarily connected to earth. On raising the plate away from the disc its potential becomes +ve, and it has therefore acquired a +ve charge.

Electrical Screening.—The lines of force proceeding from an insulated charged body placed within a room terminate on the walls of the room (unless the room is artificially insulated). No lines of force proceed into the space beyond the walls. The outer space is said to be screened from the electric lines of force within the room. Similarly, the walls will screen the inner space from all electric forces originating from outside.

Any earth-connected conductor will serve as an electrical screen to a more or less limited extent.

The Potential is the same at all points of an Insulated Conductor. For, if not, electricity will flow between various points until all are at the same potential.

Seat of the Charge.—The charge on a conductor is restricted to the outer surface. There is no charge inside a conductor (solid or hollow).

Total Amount of Induced Charge.—By enclosing the charged body inside a hollow insulated conductor (Faraday's ice-pail experiment), it is proved that the total induced charge is equal and opposite to the inducing charge.

The Potential inside a charged hollow Conductor is uniform.

The Distribution of Charge on the Surface of an Insulated Conductor.—Although the potential is the same at all points of an insulated conductor, yet the distribution is not necessarily uniform, but depends upon the shape of the conductor.

The distribution on the surface of a sphere is uniform. On pointed bodies the charge tends to accumulate at the points, and the sharper the points the more does the charge accumulate there.

Electrical Density.—*The quantity of electricity on each sq. cm. of surface is termed the density of the charge.*

The Law of Inverse Squares. Proposition I.—*The force exerted by a charged body on a neighbouring test-charge is directly proportional to the quantity of electricity on the charged body.*

Proposition II.—*The force exerted by a charged body on a neighbouring test-charge is inversely proportional to the square of the distance.*

QUESTIONS ON CHAPTER XII

1. Describe an experiment to show that when an insulated conductor is electrified by induction two opposite charges are induced on it, that which is further from the inducing charge being of the same kind. (Lond. Matric. 1896.)

2. If you were given a negatively electrified stick of sealing-wax and two metal balls mounted on insulating supports, how would you, with this apparatus, charge the balls with opposite kinds of electricity? How could you afterwards find out whether you had charged the balls as you intended, and whether their charges were equal or unequal? (1887.)

3. Explain the action of an electrophorus. (C.U.L.S. 1898.)

4. If a metal tray is supported on a dry glass, and a sheet of foolscap is thoroughly dried, rubbed with the finger-nails, and placed on the tray, a spark may be drawn from the tray. If the paper is now taken

off, the operator not touching the tray, a second spark may be obtained. Explain how these charges are formed.

(Lond. Matric. 1896.)

5. Describe how to arrange an experiment so that a conductor charged all over with negative electricity may nevertheless receive a further charge of negative electricity on being connected with the ground by a conducting wire. (1896.)

6. Having given a gold-leaf electroscope and a piece of ebonite and cat's-skin, what experiments would you make to determine whether the electrical charge on a given charged insulated body were positive or negative? (Lond. Matric. 1890.)

7. A rod of sealing-wax and a piece of flannel, after having been rubbed together, are insulated and placed some distance apart. How do their potentials differ from each other and from the potential of the earth? How would you prove the truth of your answer? (1897.)

8. An insulated conductor, A, is brought near to the cap of a gold-leaf electroscope which has been charged positively. State and explain what will happen (1) if A is unelectrified; (2) if it is charged positively; (3) if it is charged negatively. (1887.)

9. The top of an electroscope is coated with sealing-wax, which is rubbed by flannel held in an insulating support. Describe and explain the behaviour of the leaves (1) while the rubbing is in progress; (2) when the flannel is removed. (1896.)

10. Describe an experiment to prove that two parts of the same conductor may be differently electrified although they are at the same potential. (1895.)

11. Four precisely similar insulated metal balls, A, B, C, D, are placed in a row. The two inner balls (B and C) are in contact, and the distances AB and CD are equal. If A and D are electrified, what will be the electrical states of B and C after first one and then the other has been removed from the neighbourhood of A and D (1) when the charges on A and D are equal and opposite, (2) when the charges are equal and similar? (1892.)

12. Two equal insulated uncharged spheres, B and C, are placed on opposite sides of, and at equal distances from, a charged sphere A. What is the electrical state of B and C, and what will happen if the part of B nearest to A is connected by a fine wire with the part of C farthest from A? (1890.)

13. The cap of a gold-leaf electroscope, resting on an insulating stool, is joined by a wire to the gas-pipes. How will the leaves be affected when a charged glass rod is brought near to the electroscope? Give reasons for your answer. (1894.)

14. The extremity B of a wire AB is attached to the plate of a gold-leaf electroscope. By means of an insulating handle, the other end A is placed in contact first with the blunt and then with the more pointed end of a pear-shaped insulated and electrified conductor.

Describe and explain the movements of the leaves of the electroscope. (1889.)

15. Describe an experiment to prove that the charge on an electrified conductor lies wholly on the surface.

(Lond. Matric. 1897.)

16. An insulated conductor A is charged with electricity. Another conductor B, earth-connected, is placed near to A. Is the induced charge on B greater than, equal to, or less than the charge on A? Give reasons for your answer. (1890.)

17. How may it be experimentally proved that external electrified bodies produce no electrical force within a hollow conductor?

(1895.)

18. An electrified metal ball is introduced into a dry glass tube closed at one end, and then, the tube being held in the hand, is brought near to the cap of the electroscope. What will the effect on the electroscope be if the exterior of the tube (1) is, (2) is not, covered with tinfoil? (1889.)

19. Describe Faraday's ice-pail experiment, and show how it may be inferred from it that the total quantity of electricity induced by a given charge is equal and opposite to the charge.

(Lond. Matric. 1890.)

20. Into an insulated uncharged metal jar standing on the cap of an electroscope an electrified brass ball is lowered without contact; the jar is then touched for a moment with the finger, and the ball is next allowed to touch the jar, after which it is removed. Explain the various effects produced on the gold leaves. (1898.)

21. An insulated hollow metal vessel has a charge of positive electricity and is at some distance from other conductors. An uncharged metal ball, supported by a silk thread, is (1) introduced into the vessel without touching it, (2) connected momentarily with the earth, and (3) removed to a distance. State how its potential changes during these operations. (1891.)

22. Under what circumstances is it possible to transfer the whole of the charge on a conductor to another insulated conductor? (1891.)

23. Two pith-balls hang side by side by two damp cotton threads. State and explain what happens when an excited glass rod is brought gradually near the two pith-balls from below. (1885.)

24. To protect a gold-leaf electroscope from being acted on when an electrical machine is at work near it, it is sufficient to cover the electroscope with a thin cotton cloth. How is this? (1886.)

25. The caps of two gold-leaf electroscopes A and B are connected by a long wire, and a positively charged sphere is brought near A. What will be the indications of the electroscopes, and how will they alter if either A or B is touched? (1902.)

CHAPTER XIII

CAPACITY—CONDENSERS—LEYDEN JARS

Apparatus required.—Insulated spheres (or tinfoil-coated bottles) of different sizes. Hollow can. Insulating stand. Gold-leaf electroscope. Insulated tinfoil roller-blind. Electrophorus. Soap-bubble apparatus. Two insulated metal discs of different size. Proof plane. Simple condenser. Pith-ball electroscope. Leyden jar. Discharging tongs. Skeleton Leyden jar. Leyden jar battery. Wimshurst machine. Universal discharger. Sheet of thin glass and narrow glass tubing. Gunpowder. Tinfoil.

Capacity of a Conductor.—When two insulated conductors, one of which is charged, are brought into contact, the charge spreads over both conductors. The uncharged conductor becomes charged as we have learnt, but we do not as yet know what fraction of the original charge has been transferred to it. We may safely anticipate that the amount which is transferred will depend upon the size of the uncharged conductor—we should expect a larger conductor to receive a larger fraction of the original charge than would be the case if the conductor were small.

We know that the *potential* of the two conductors will become the same as soon as they are brought into contact, but it does not follow that the quantity of electricity will be the same on each. We should, of course, expect the final potential to be less than that of the charged body before contact was made, since the same number of lines of force which formerly originated from the charged conductor will now be distributed

over a larger area. These points may be investigated by the following experiments.

EXPT. 99.—Obtain two or three metal spheres of different sizes, each mounted on an insulating support. (Instead of the spheres, bottles of different sizes may be used, see footnote, p. 172.) Place a hollow can on the top of the electroscope disc. Charge one of the spheres by means of an electrophorus, and touch it with an uncharged sphere. Both spheres are now charged to the same potential. Convey the larger sphere to the electroscope, lower it into the can, and allow it to touch the inner surface. The whole charge is now transferred to the can and electroscope. Withdraw the sphere, and observe the divergence of the leaves. Discharge the electroscope. Proceed in the same manner with the smaller sphere. Notice that the divergence is much less. Hence the larger portion of the charge was on the larger sphere. We say that the spheres have not the same *capacity* for electricity.

The *capacity* of a conductor evidently depends upon its size; and a larger conductor evidently requires more electricity to raise it to a given potential than a smaller conductor will require.

The capacity of a conductor is measured by the quantity of electricity which must be given to it in order to raise its potential to a given amount.[1]

$$\text{Or, Capacity} = \frac{\text{Quantity of electricity (Q)}}{\text{Potential to which it is raised by Q}}.$$

From this definition we see that if the capacity of a conductor increases while the quantity of electricity on it remains constant, then its potential will become less.

[1] (i.) A small insulated conductor is charged with *unit* **Quantity** of electricity when it is repelled with a force equal to 1 dyne by a similar conductor charged with an equal quantity and placed 1 centimetre distant.

(ii.) An electrified body has *unit* **Potential** when 1 erg of work must be done in conveying an insulated conductor, charged with unit quantity, from a great distance up to the surface of the electrified body.

(iii.) An insulated conductor has *unit* **Capacity** when unit quantity of electricity is required to raise its potential through one unit.

EXPT. 100.—Connect a large insulated sphere to the electroscope by means of a long thin wire. Give a *small* charge to the sphere by means of the electrophorus. Notice the divergence of the leaves. Bring an insulated uncharged sphere into contact with the charged sphere. Observe the diminution of the divergence, showing that, although the total quantity of electricity is the same, the potential is less. Repeat the experiment, using a larger uncharged sphere, and observe the greater diminution of divergence.

The same result may be obtained by the following method :—

EXPT. 101.—(i.) Make a tinfoil roller-blind by fixing one end of a sheet of foil (30 cms. × 20 cms.) to a piece of wide glass tubing. Insert corks in both ends of the tube, and fix a wire-nail through the axis of each cork. The glass roller is supported by the nails resting on the bent ends of two glass uprights, the lower ends of which pass through the corks of two bottles weighted with sand. The blind can be rolled up and down by attaching the end of a silk thread to one of the corks, and winding it round the end of the roller (see Fig. 128). The blind is thus an insulated conductor. Connect one of the lower corners of the blind to the disc of an electroscope by means of a long thin wire. Charge the blind by means of the electrophorus.

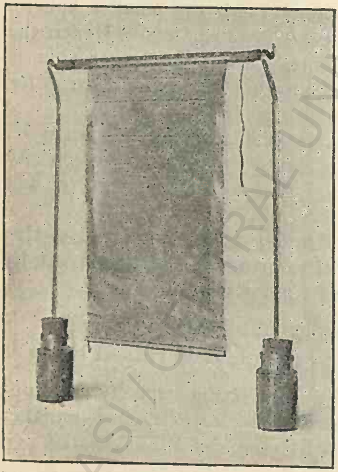


FIG. 128.—To illustrate Expt. 101 (i.).

Observe the divergence of the leaves. Pull the thread, and slowly roll up the blind; observe how the divergence increases. The charge is restricted to the outer surface, so that as the blind is rolled up the charge is distributed over a much smaller area; the surface, and therefore the capacity, of the conductor is less. The quantity of electricity remains the same, hence the potential will be raised, and will cause an increased divergence of the

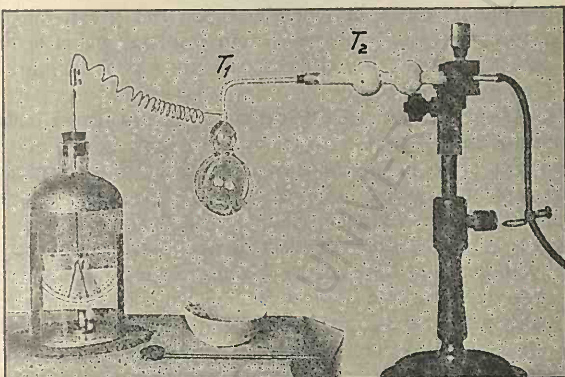


FIG. 129.—To illustrate Expt. 101 (ii.).

leaves. Lower the blind, and notice how the leaves partially collapse.

The same result may be arrived at by using a charged insulated soap-bubble.

(ii.) Bend a thistle-headed glass tube at right angles; attach to it a wide glass tube filled with granulated calcium chloride, to the other end of which is connected a length of narrow rubber tubing provided with a metal clip. Support the glass tube on an insulating stand (or paint the outside of the tube with melted paraffin-wax to ensure good insulation, and fix the tube in an ordinary wooden clamp) (Fig. 129). Wrap a thin copper wire two or three times round the thistle tube, and turn the free end inside the thistle head; connect the other end

of the wire to an electroscope. Raise a small dish of soap solution until the thistle head dips into the solution; remove the dish; open the clip, and blow a *small* soap-bubble. Charge the bubble, and observe the divergence. Blow the bubble larger, and observe the diminution of divergence. Now suck the air out of the bubble, and observe the increase of divergence. The capacity of a large soap-bubble is evidently greater than that of a small bubble.

The changes in divergence are not great, and are more successfully observed if an insulated paper scale is placed inside the electroscope and just behind the leaves (Fig. 129).

The Capacity of a Conductor depends upon neighbouring Conductors.—So far we have only considered the relationship between the capacity and the size of a conductor. Is the capacity affected in any way by the presence of neighbouring conductors (either insulated or earth-connected)?

EXPT. 102.—Charge an electroscope +ly. Observe the divergence of the leaves. Hold the hand just above the disc, and observe how the divergence is less than before. When the hand is removed the divergence increases to its original value. The conductor (*i.e.* the disc and leaves of the electroscope) did not change in size, nor did the quantity of electricity on the conductor alter, yet the potential was reduced. Evidently the "capacity" of the conductor was increased by holding the hand over the disc.

The diminution of potential is explained by remembering that the +ve charge on the electroscope will induce a −ve charge on the under-surface of the hand. This induced −ve charge will create a region of −ve potential in its neighbourhood, thus causing a reduction of the +ve potential of the electroscope (see Fig. 111, *h*).

EXPT. 103.—(i.) Hold an insulated metal plate over the disc of a +ly charged electroscope. The −ve charge induced on the lower surface of the plate tends to *lower* the potential in the region round the electroscope, while the +ve charge induced on the upper surface tends to *raise* the potential. Since the former is nearer to the

electroscope than the latter, the *diminution* will slightly exceed the *increase*. Hence the potential of the electroscope is lowered very slightly. Observe the slight diminution in the divergence of the leaves. The thicker the metal plate the more distant will be the induced +ve charge, hence a thicker plate will diminish the potential of the electroscope more than a thin plate.

(ii.) Touch the metal plate while still holding it in the same position. The divergence of the leaves is reduced still more. The induced +ve charge has disappeared, and no longer tends to raise the potential. The result is exactly the same as holding the hand at the same distance above the disc of the electroscope (see Fig. 111, *h*).

The tendency of the lines of force to accumulate on the side of the charged conductor facing the earth-connected conductor may be verified in the following manner:—

EXPT. 104.—Charge an insulated sphere; the density of the charge is uniform. Hold a metal plate in the hand and near to the sphere. Touch the near side of the sphere with a proof plane, and test the density of the charge by means of an electroscope. Observe the divergence, and discharge the electroscope. Test the distant side of the sphere in the same manner, and observe that the density is much less. Hence the charge has become *accumulated* on the side facing the earth-connected conductor.

This tendency of the charge to accumulate (or to become *piled up*) owing to the presence of a neighbouring earth-connected conductor is termed the *condensing of electricity*, and any arrangement of conductors which fulfils this condition is termed **a condenser.**

A condenser may be defined as **any arrangement by which the capacity of a conductor is artificially increased.**

From Expt. 103 *we see that the most favourable arrangement for a condenser is to bring an earth-connected conductor near to an insulated charged conductor.*

Condensers.—Upon what conditions does the capacity of a condenser depend? Does it depend in any way upon the size of the conductors, or upon the distance apart, or upon the

medium which separates the two conductors? The following experiments will help to answer these questions.

EXPT. 105.—Charge an insulated sphere, which is connected to an electroscope by means of a long thin wire. Hold in the hand a disc of metal, much smaller in diameter than the sphere, about 3 or 4 cms. away from the sphere. Observe the diminution of divergence. Remove the small disc, and hold a much larger disc at the same distance as before. The divergence is diminished much more than before. Hence the larger disc has caused a greater diminution of potential—or, in other words, the capacity of the condenser is much greater when the large disc is used.

Hence, **capacity depends directly upon the area of surface of the two conductors.**

EXPT. 106.—Using the larger metal disc as in Expt. 105, now vary the distance. Observe that, as the disc is gradually moved *towards* the sphere, the potential gradually diminishes.

Hence, **the capacity of a condenser is greater when the distance separating the conductors is diminished; or, the capacity is inversely proportional to the distance apart.**

In future experiments it is better to use a more elaborate form of condenser, consisting of two vertical metal plates (about 15 cms. square) fastened to horizontal rods of sealing-wax, to serve as insulating supports (Fig. 130). The plates are readily made of sheet zinc or copper.

EXPT. 107.—Connect plate A to an electroscope by means of a long thin wire, and connect B to earth. Charge the plate A. Observe the divergence when B is about 20 cms. distant from A. Slowly move B towards A, and observe the diminution of divergence. Slowly remove B, and observe the gradual increase of divergence. The plates A and B constitute a simple form of condenser, in which the capacity of A is artificially raised by the presence of B.

EXPT. 108.—(i.) Place B about 3 cms. from A, and charge A. Carefully insert a square slab of paraffin-wax (about 1 cm. thick, and about the same area as the plates)

between A and B. Notice the diminution of divergence, and how it increases to its original value when the slab is removed. (The diminution will be comparatively small, and will require careful observation.)

(ii.) Insert a slab of plate-glass (6 to 8 mms. thick) between A and B. The diminution of the divergence is much more marked than when paraffin-wax was used.

We thus see that **the capacity of a condenser depends largely upon the medium through which the lines of force pass.** The medium is generally termed the **dielectric,** because the electrical forces between the plates are transmitted *through* the medium.

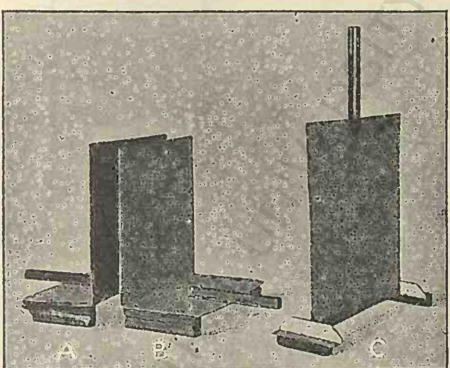


FIG. 130.—A simple form of condenser (as used in the Elementary Physical Laboratory, The Owens College, Manchester).

In these experiments the effect of replacing a portion of the air by paraffin-wax or glass is the same as if the conductors had been brought still nearer together. The wax and the glass seem to transmit the force more readily than air. This varying power of transmitting the lines of electric force is termed the **Specific Inductive Capacity (S.I.C.).** The **S.I.C.** of glass is greater than that of wax, and that of wax is greater than that of air. Nearly all insulating solids have a higher **S.I.C.** than air.

The Field of Force of a Simple Air-Condenser

(i.) *Lines of Force.*—When the simple condenser used in Expt. 107 is charged, and the two plates are close together, nearly all the lines of force pass through the intervening air-space from A, which has + ve potential, to B, which has zero

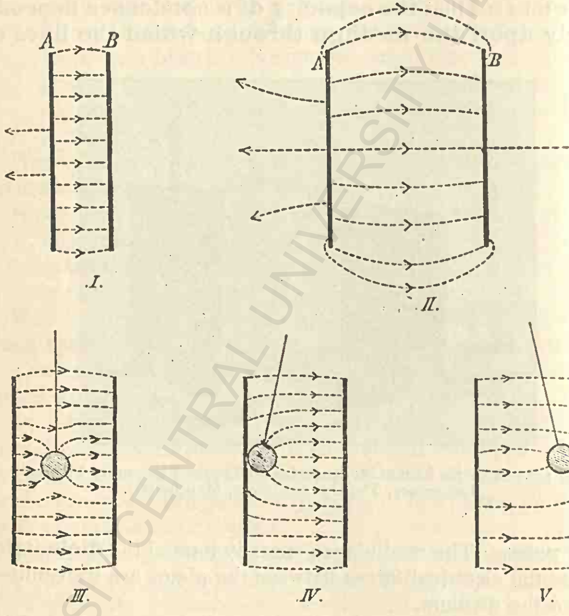


FIG. 131.—The field of force due to a simple condenser.

potential. A *few* lines of force may proceed from the outer surface of A towards the walls of the room (Fig. 131, i.). If B is now insulated and removed to a distance, far more lines of force will pass from A towards the walls of the room, and fewer will pass through the dielectric. Some lines will pass from the walls of the room to the outer surface of B. Thus, there will be a small *free charge* on both plates, + ve on A and − ve

on B (Fig. 131, ii.). If the plates are removed to a much greater distance apart, then the charges on each plate will be uniformly distributed over both surfaces.

Fig. 131 (iii.) represents the field of force and a pith-ball suspended in the field by means of a silk fibre. It serves as a *conducting bridge* for some of the lines of force between A and B. If nearer to A it will be drawn towards it; and when in contact with A it will be attracted by B (Fig. 131, iv.). At each contact with a plate the lines of force between the ball and the plate will be destroyed. Thus Fig. 131 (v.) represents the lines of force which will remain after touching the plate B. The pith-ball will swing to and fro until the condenser is discharged.

Expt. 109.—Charge the condenser, and suspend a gilt pith-ball by means of a silk fibre in the field between the plates. Notice the vibration of the ball between the plates.

If both plates are placed as in Fig. 131 (i.), and B is insulated after A has been charged, then the condenser can be slowly discharged by alternately touching A and B with the finger, beginning with A. This may be explained in the following manner. When A is touched, the lines of force on the distant side, which represent the so-called *free charge*, will be destroyed, and they will be replaced by other lines of force which formerly traversed the dielectric towards B; an equal number of lines on B will consequently be set free, which will be destroyed when B is touched. This will cause a small free charge on A, which will be discharged at the next contact with the finger. Thus, the total number of lines of force between A and B is gradually diminished; the condenser is discharged by *alternate contacts.* This may be experimentally verified in the following manner:—

Expt. 110.—Make a hoop (about 8 cms. diameter) of thin copper wire with the two ends about 3 cms. apart. Fix gilt pith-balls on the ends of the wire. Suspend this from an earth-connected support, so that it can swing to and fro like a pendulum (Fig. 132). Place the condenser plates between the pith-balls, and as close together as possible. Earth-connect B, and charge A. Now insulate B, and separate the plates slightly. The

pith-balls swing to and fro, alternately touching A and B, until the condenser is discharged.

The attraction of the pith-balls proves that there are *some* lines of force proceeding from the outer surface of the plates. Since the pith-balls are earth-connected, the experimental result is the same as though the plates had been alternately touched with the finger.

(ii.) *Potential.* — When the condenser is charged the potential of A is +ve and that of B is zero. Hence the

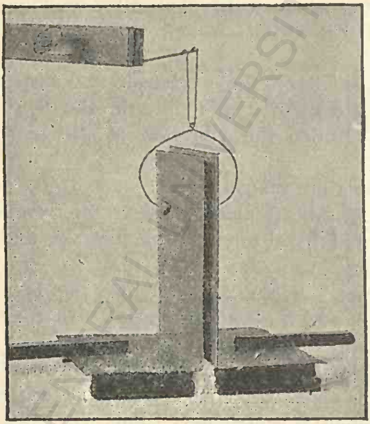


FIG. 132.—To illustrate Expt. 110.

potential diagram would resemble Fig. 133 (i.). The potential would gradually diminish in value as we proceed from A to B. Outside A the potential will slowly fall, and become zero at the walls of the room.

If B is now disconnected from the earth, and removed to a greater distance from A, its induced – ve charge will now give to it a – ve potential. Points nearer to A will have a higher + ve potential than before, and points nearer to B will now have a – ve potential. At some intermediate point the potential will be zero. If the plates were very close together when the condenser was charged, the + ve and – ve charges on A and

B will be approximately equal in amount; in this case the point of zero potential will be midway between A and B (Fig. 133, ii.). Outside the plate A there will be a region of + ve potential gradually diminishing to zero; outside B there is a region of – ve potential which gradually increases to zero at the walls of the room.

EXPT. 111.—(i.) Charge the condenser, with the plates about 8 cms. apart. Connect the plate C (Fig. 130) to an electroscope by means of a thin wire; holding it by its

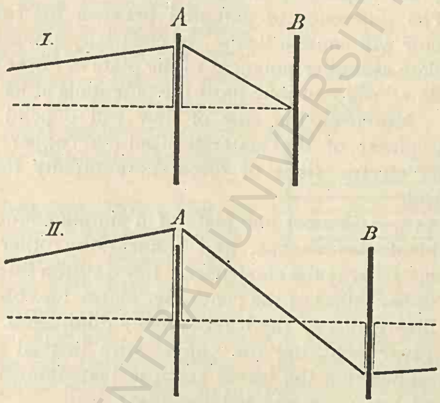


FIG. 133.—Potential diagram of a simple condenser.

insulating handle, place it between A and B, and parallel to both. Observe that the divergence is greater when C is nearer to A, and gradually diminishes as it is moved towards B. While C is in position, remove the connecting wire by means of an insulating handle, and verify that the charge on the electroscope is + ve.

(ii.) Move C to a distance, and connect up to the electroscope again. Without discharging A or B, move B about 16 cms. away from A. Explore the field between A and B as before. The leaves diverge when C is near A, and gradually collapse as C is moved towards B; when moved still nearer to B the leaves again

diverge. Now remove the connecting wire, and verify the – ve charge in the electroscope, showing that the region near to B is one of – ve potential.

Transfer of Electricity through a Conductor.—In Expt. 109 a movable conductor, in the form of a pith-ball, was used in order to transfer the electrical charge from one plate of the condenser to the other, and so to equalise their potentials (or, in other words, to remove the electric lines of force between the plates). The same result may be obtained by connecting the oppositely charged plates by means of a *conductor*. The difference of potential between the two ends of the conductor will cause a "flow" of electricity along its length from the plate at higher potential to the plate at lower potential, and the "flow" will continue until the potentials at its two ends are equal. Moreover, the *rate* of flow will depend upon the conducting power of the material used—a copper wire will remove the electric lines of force more rapidly than will a cotton thread.

EXPT. 112.—Connect one plate of a simple condenser to a gold-leaf electroscope, and connect the other plate to earth. Charge the condenser. Lay a cotton thread across the upper edges of the condenser plates, and observe that the divergence of the leaves *slowly* diminishes. Repeat the experiment, but use copper wire instead of cotton, and notice that the leaves collapse instantaneously when the plates are connected together.

Disruptive Discharge. EXPT. 113.—Slowly bring the knuckle near to a charged electrophorus disc; when at a short distance a feeble spark passes between the disc and the knuckle. The insulating power of the air has broken down, and the disc has been discharged by *disruption of the dielectric*.

The lines of force from the disc were concentrated in that region towards which the knuckle was pointing. The nearer the knuckle the greater the concentration; and when the concentration reaches a certain limit the tension of the lines of force overcomes the insulating power of the air, and a discharge of electricity takes place between the disc and the knuckle. We say that *the electric strain overcame the dielectric strength of the air.*

Most insulating solids and liquids have a much greater dielectric strength than air; the dielectric strength of oil is five times as great as that of air. If, in Expt. 113, we had separated the knuckle from the disc by a sheet of thin glass, mica, or paraffined paper, it would have been possible to bring the knuckle much nearer without causing disruptive discharge. Therefore the plates of a condenser may be placed much nearer together if a solid dielectric is used.

Usual Form of Condenser.—The most usual form of condenser consists of a large number of sheets of tinfoil separated from each other by sheets of paraffined paper; alternate sheets of the foil are connected together, so that the area of surface of the two conductors is many times greater than that of a simple two-plate condenser (Fig. 134).

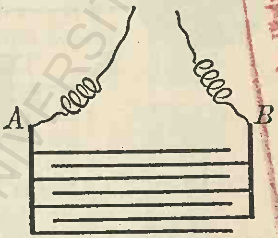


FIG. 134.—Diagram of ordinary form of condenser.

The Leyden Jar.—This is a simple form of condenser which derives its name from the fact that it was first used by Van Musschenbroek, a professor at Leyden, in Holland. It consists of a glass jar, coated outside and inside with tinfoil to within 2 or 3 cms. of the top. It may therefore be regarded as a condenser consisting of two parallel plates separated by a glass dielectric. The jar is provided with a wooden lid, through the centre of which passes a brass rod, terminating above in a brass knob; a short length of metal chain is attached to the lower end, and of sufficient length to touch the tinfoil lining. The tinfoil lining serves as the insulated conductor, which may be conveniently charged through the knob; the jar is either placed on a table or held in the hand, so that the outer coating is consequently earth-connected (Fig. 135).

EXPT. 114.—Place a Leyden jar on the table. Bring the charged disc of an electrophorus into contact with the knob; repeat this five or six times. The jar is now charged. Hold the knuckle near to the knob, and observe the slight shock which is felt when the spark passes.

As a rule it is advisable *not* to discharge the jar through the body in this manner, since a powerful discharge may have serious consequences. A safe method of discharging the jar is afforded by the **discharging tongs** (Fig. 135), which consist of a jointed brass rod with brass balls at each end, and provided with glass handles. To use the tongs, place one knob in contact with the outer coating, and bring the other knob towards the knob of the jar.

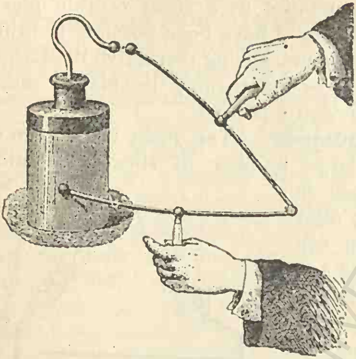


FIG. 135.—Leyden jar and discharging tongs.

A much simpler method of charging the jar is to bring the knob into contact with a terminal of a Wimshurst machine (see Fig. 141), the other terminal of which is connected to the nearest gas or water pipe. In subsequent experiments it will be assumed that this method of charging is adopted.

Residual Charge of a Leyden Jar. EXPT. 115.—Charge a Leyden jar, which is standing on a table; bring one knob of the discharging tongs in contact with the outer coating of the jar, and gradually bring the other knob near to the knob of the jar as though to discharge it. As soon as a spark passes, remove the tongs. After a short interval a second spark, shorter than the first, will be obtained; and it may be possible to obtain a third and fourth spark. These subsequent discharges are said to be due to the *residual charge*.

The glass dielectric is in a strained condition, from which it does not recover instantaneously when the first spark passes; a portion of the original strain remains, and this enables a second spark to be obtained. The phenomenon may also be explained as due to the fact that glass is not an absolutely perfect insulator, and that the charges on opposite sides of the glass are to a slight degree drawn into the substance of the

glass itself. Only that portion which remains on the surface of the glass is discharged by the first spark, after which the charges inside the glass slowly return to the surface, and give rise to the subsequent sparks.

Seat of the Charge of a Leyden Jar. EXPT. 116.—

(i.) Use a Leyden jar of which the coatings can be readily removed (Fig. 136). Charge the jar. Lift out the inner coating by means of the discharging tongs, and place it on the table. Lift out the glass jar. Replace the glass jar, and also (*by means of the tongs*) the inner coating. A powerful discharge may be obtained.

(ii.) Recharge the jar, and separate the parts as before. Hold the glass jar in the left hand, and insert the right hand inside the jar so as to touch the sides. Notice the numerous slight discharges which are obtained. Replace the parts, and verify that the jar is now discharged.

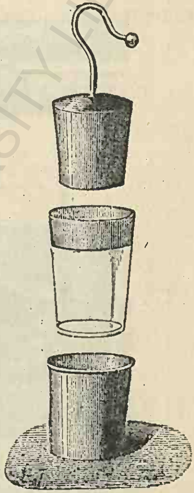


FIG. 136.—Skeleton Leyden jar.

Evidently the opposite charges are distributed over the surfaces of the glass, and are not confined to the metal coatings.

Leyden Jar Battery.—In order to obtain more powerful effects, a number of jars may be placed together inside a box lined with tinfoil. The knobs are all connected together by metal bars, and the outer coatings are connected together by the tinfoil lining in the box. The arrangement now has the capacity of one immense jar, and is termed a **Leyden Jar Battery** (Fig. 137). The lining to the box is connected by a wire to the nearest gas-pipe. Fig. 138 represents the method of discharging a jar through a **Universal Discharger**, which consists of two brass rods supported by ball-and-socket joints on the top of glass uprights.

The properties of the discharge from a Leyden jar battery may be shown by the following experiments :—

EXPT. 117.—(i.) Insulate a sheet of thin glass, and place it between the metal points of a universal discharger. The discharge may be sufficiently intense to puncture the glass. If the sheet is small the discharge may pass round the edge of the glass in preference to the shorter path through the glass. This may be prevented by

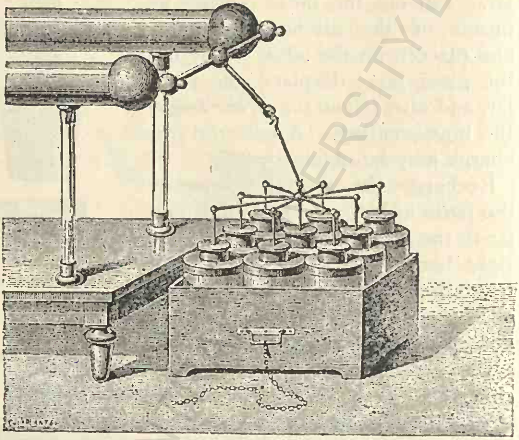


FIG. 137.—A Leyden jar battery.

fixing a short length of narrow glass tubing to the centre of the glass plate by means of sealing-wax; the wax must not occupy the bore of the tube, but must form the joint outside the tube. A piece of thick copper wire, slightly longer than the tube, is placed inside the tube, one end touching the glass plate, and the other end touching an arm of the discharger.

This phenomenon sometimes occurs in the process of charging a Leyden jar when the discharge punctures the glass jar and renders it useless. This is likely to occur if the tinfoil coatings are not sufficiently high to allow the discharge to pass round the outside of the neck of the jar in preference to puncturing the glass.

(ii.) Place a small heap of gunpowder on a suitable stand between the points of the discharger. The spark will not fire the gunpowder, but will scatter it in all directions. Repeat the experiment, but connect one arm of the discharger to the tongs by means of a short piece of wet thick string, which, being a poor conductor, hinders the rapidity of the discharge. The gunpowder now ignites, showing that when the mechanical disturbance

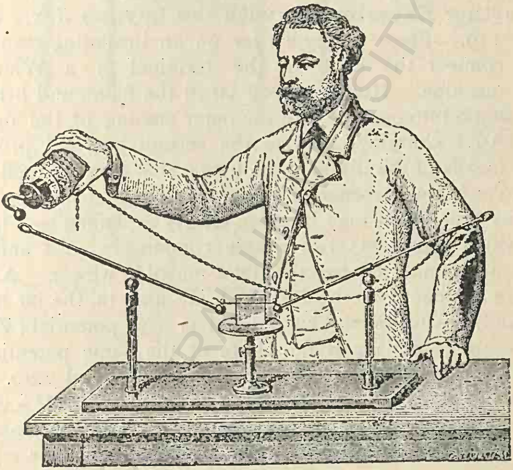


FIG. 138.—A universal discharger.

due to the spark is lessened the *heat* of the spark is sufficient to ignite the powder.

(iii.) The same effect may be shown by connecting the arms of the discharger by means of a short narrow strip of tinfoil (about 0.5 mm. wide). The spark will completely destroy the foil.

To charge a Leyden Jar negatively from the Positive Terminal of a Wimshurst Machine.

EXPT. 118.—Place a Leyden jar on an insulating stand. Connect the inner coating of the jar to earth by means

of a wire, and connect the outer coating to the terminal of the machine. The outer coating receives a +ve charge from the machine, and induces a −ve charge on the inner coating. Quickly remove, by means of an insulating handle, the wire connected to the machine, and then remove the earthed wire. The outer coating may now be held in the hand, and the jar removed to the table. Verify the −ve charge on the inner coating by touching the knob with a proof plane.

Further Experiments with the Leyden Jar. EXPT. 119.—Place a Leyden jar on an insulating stand, and connect the knob to the terminal of a Wimshurst machine. Hold a second jar in the hand, and bring the knob into contact with the outer coating of the first jar. After charging, remove the second jar, and prove, by means of the discharging tongs, that it is charged; also verify the presence of a charge in the first jar.

This experiment may be more clearly explained by Fig. 139 (i.), which represents two simple condensers, AB and CD, which are connected together by a movable wire a. AB and CD are analogous to the insulated jar and to the jar held in the hand. After being charged A has +ve potential (V), and D has zero potential; B and C are at the same potential (v), which is +ve, and intermediate between V and *zero*. The *quantity* of electricity on AB will be proportional to $(V - v)$, and that on CD will be proportional to $(v - o)$. If the glass is of equal thickness in both, then the potential v will be equal to that of a point midway between A and D, or $v = \frac{V}{2}$. The separation of the jars is analogous to breaking the connecting wire a.

Fig. 139 (ii.) represents the potential diagram when the glass is equally thick in both jars. The line *abcd* represents the fall of potential through the two jars. If the glass is thicker in the first jar than in the second, then the potential diagram will be changed to Fig. 139 (iii.).

EXPT. 120.—Charge a Leyden jar, holding the knob 1 cm. away from the terminal of the machine. Discharge it. Again charge the jar, holding the knob *in contact* with the terminal. Discharge it, and notice that the jar is

more fully charged than in the former case. This difference is due to the fact that in the former case the knob does not acquire the same potential as the terminal,

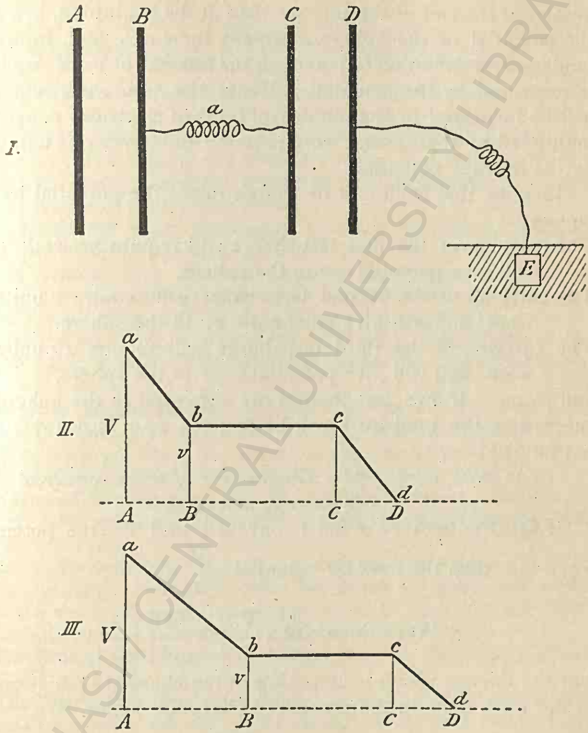


FIG. 139.—To illustrate Expt. 119.

because sparks cease passing across the air-gap when the *difference of potential* is insufficient to overcome the dielectric strength of the air. In the second case the knob acquires the *same* potential as the terminal, and therefore receives a larger charge.

The Energy of a Charge.—Imagine that a large insulated sphere is charged by successive small charges of 1 unit each, conveyed on a small insulated sphere from a distance. The work required in order to carry a unit charge will be greater at the end of the process than at the beginning, because the potential of the sphere gradually increases, and, from the fundamental definition of potential, the amount of work required is measured by the potential. Hence the *total* work required will be measured by the number of units of electricity conveyed multiplied by the *average* work required to convey one unit (*i.e.* by the average potential).

Imagine that each unit of charge raises the potential by an amount v.

The carrying of the first test-charge will require *no* work, and will give potential $= v$ to the sphere.

The carrying of the second test-charge will require v units of work, and will give potential $= 2v$ to the sphere.

The carrying of the third test-charge will require $2v$ units of work, and will give potential $= 3v$ to the sphere,

and so on. If five test-charges are conveyed to the sphere in succession, the total work will be $(0 + v + 2v + 3v + 4v) = 10v = (5 \times 2v)$; or,

The total work done = The number of units conveyed × The average potential.

If Q = the number of units conveyed, and V = the potential when full, then the *average* potential $= \frac{V}{2}$.

$$\text{Work done} = Q \times \frac{V}{2} \left(\text{or } \frac{QV}{2}\right).$$

But the energy which is stored up in the charged body is equal to the work done in the process of charging, hence

$$\text{Energy} = \frac{QV}{2};$$

or, **the energy of a charge is equal to one-half the product of the quantity and the potential.**

$\left(\text{Since } V = \frac{Q}{C},\right.$[1] $\left.\text{the energy may also be written} = \frac{1}{2}\frac{Q^2}{C}.\right)$

[1] See p. 187.

Chief Points of Chapter XIII

The Capacity *of a conductor is measured by the quantity of electricity which must be given to it in order to raise its potential to a given amount.*

$$\text{Capacity} = \frac{\text{Quantity of electricity.}}{\text{Potential to which the conductor is raised.}}$$

The capacity of a conductor depends upon (i.) *its size* and (ii.) *the presence or absence of neighbouring conductors.* A large conductor requires more electricity to raise it to a given potential than a smaller conductor. The capacity of a conductor is increased by the presence of a neighbouring uncharged conductor, and the increase is greater when the latter is earth-connected.

A Condenser is any arrangement by which the capacity of a conductor is artificially increased.

The capacity of a condenser depends directly upon the area of surface of the two conductors, inversely upon their distance apart, and is also dependent upon the medium between the conductors.

Different insulating substances have different powers of transmitting electric lines of force. This power is called the *Specific Inductive Capacity.*

Electric Discharge may take place by means of (i.) a movable carrier, (ii.) through a conductor. It may take the form of a *disruptive discharge,* when the electric strain overcomes the dielectric strength of the medium.

Forms of Condensers.—(i.) *The Leyden Jar* consists of a glass jar coated inside and outside to within a short distance of the edge with tinfoil.

(ii.) A frequent form of condenser consists of numerous sheets of tinfoil, insulated from each other by means of paraffined paper. Alternate sheets are connected together so as to form two large conductors placed close together and insulated from each other.

The Seat of the Charge in a Leyden jar is on the surfaces of the glass, and not on the metal coatings.

The Disruptive Discharge from a Leyden jar has considerable penetrative power, and can pierce through a sheet of glass. It is capable of effecting mechanical disruption in other ways, and also generates much heat.

The Potential to which a Leyden jar is charged by a Wimshurst machine is greater when the knob actually touches the terminal.

Questions on Chapter XIII

1. Describe how to make and how to use an electric (electrostatic) condenser. (Lond. Matric. 1898.)

2. A Leyden jar is held in the hand by its outer coating, and the knob is presented to the prime conductor of an electrical machine in action. Describe the resulting charged condition of the jar, and explain why it is safe to put the charged jar down on the table. Explain why you receive a shock on touching the knob when the jar is standing on the table, but not so when you or the jar stand on a dry cake of resin. (Lond. Matric. 1897.)

3. An electrified drop of water, supported by a non-conductor, evaporates. Assuming that the vapour is not electrified, what changes will the potential of the drop undergo? (1891.)

4. Two parallel insulated metal plates, A and B, are placed a small distance apart, and one of them (A) is charged with positive electricity. Draw a picture showing the lines of electric force between and around them. How will the lines be altered when B is earth-connected?

5. Two similar vertical insulated plates, A and B, are placed parallel to each other and about an inch apart. Each is connected to the cap of a separate gold-leaf electroscope. State and explain the indications of the electroscope when (1) a positive charge is given to A, and afterwards (2) B is touched. (1898.)

6. A sheet of tinfoil is suspended by a dry silk thread and charged as highly as possible by an electrical machine, but on discharging it only a slight spark is obtained. If the tinfoil is placed on a sheet of dry glass lying on the table, a bright spark can be obtained after the tinfoil has been charged by the machine. Explain the cause of the difference. (1895.)

7. How do you explain the fact that a Leyden jar cannot be highly charged unless its outer coating be earth-connected? (1893.)

8. A Leyden jar standing on an insulating stool is electrified by a machine, while its outer coating is touched by the knob of an exactly similar Leyden jar of which the outer coating is held in the hand. The first jar is then disconnected from the machine, is taken in the hand by its outer coating, and is presented with its knob to that of the second jar. Does a spark pass? Give reasons for your answer. (1896.)

9. Describe the construction of the Leyden jar, and give reasons based (1) on experiment and (2) on theory for believing it can be used to store up a relatively large charge of electricity. (1897.)

10. The inner coating of a Leyden jar is connected by a wire with the prime conductor of an electrical machine and also with a gold-leaf electroscope. If the jar rests upon a sheet of glass, a quarter of a turn of the machine produces a large divergence of the leaves of the electroscope. If the glass be removed, ten turns of the handle are required to produce the same divergence. Explain this. (1888.)

CHAPTER XIV

ELECTRICAL MACHINES—ACTION OF POINTS—ELECTRICAL DISCHARGE

Apparatus required.—Glass cylinder machine. Wimshurst machine. Copper wire. Needles and soft wax. Candle. Metal plate with insulating handle. Gold-leaf electroscope. Hamilton's mill. Large insulated sphere. Hollow tin. Insulating stand. Apparatus for showing character of discharge through rarefied air. Sheet of cardboard. Thin string, and five pairs of pith-balls supported on cotton. Starch-paper.

An Electrical Machine.—We have found that a body may become electrified either by *friction* or by *induction.* Any mechanical appliance designed to produce these effects on a large scale is termed an *electrical machine.* The electrophorus may be regarded as a simple example of an electrical machine, depending for its action upon the principles of Statical Induction, but it is unsuited for the generation of large electrical charges.

The earliest forms of machines were mere elaborations of the simple experiment in which a rod of sulphur or resin is charged –ly when rubbed with the dry hand; at a later date glass was substituted for the sulphur, and suitable *rubbers* were used instead of the hand. Such machines may be termed **frictional** electrical machines, as distinct from **induction** (or **influence**) machines, which for all experimental purposes have almost entirely replaced the former type.

The Glass Cylinder Machine (Fig. 140).—This consists of a glass cylinder mounted on a horizontal axis which

can be rotated by means of a handle. The cylinder, when rotated, is electrified +ly by rubbing against a pad of silk or one of leather smeared with an amalgam of tin, zinc, and mercury[1] (which is lower in *frictional order* than silk). In the earlier types of this machine the electric charge was collected from the surface of the glass by a metal chain which hung against the cylinder on the opposite side to the pad. Franklin replaced the chain by a *metal comb*, the teeth of

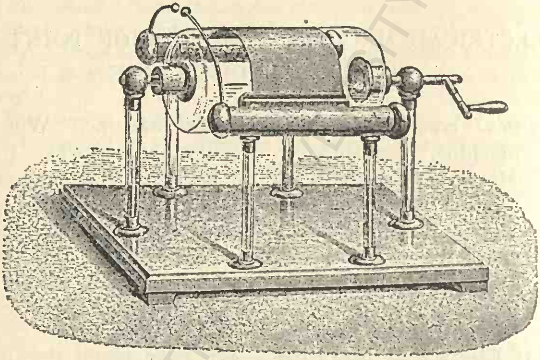


FIG. 140.—A glass cylinder machine.

which point towards and nearly touch the surface of the glass. The comb is acted upon inductively by the charged glass, and the surface density of the induced −ve charge on the teeth is naturally very high—so much so that, as Franklin discovered, a stream of air electrically charged −ly is driven from the points towards the glass (see *Action of Points*, p. 214). The −ly charged air impinges on the surface of the glass and neutralises the charge on its surface; on passing the rubber a second time the glass is again electrified.

The metal comb is usually connected to an insulated metal cylinder, over which the induced +ve charge will be distri-

[1] The amalgam is made by melting together one part by weight of tin and one part of zinc, and adding the molten alloy to two parts by weight of mercury. The amalgam is mixed with thick grease sufficient to enable it to be smeared evenly over the surface of the leather pad.

buted; the cylinder will have a high +ve potential, and will yield a constant succession of sparks when the knuckle is held near to it, since its potential will be maintained by the freshly-charged glass cylinder.

Since the glass acquires its +ve charge from the rubber, the machine will only continue to supply +ve electricity if the rubber is earth-connected by means of a wire or metal chain. If the machine is required to give −ve electricity the comb is connected to earth, and the rubber is mounted on an insulating support and provided with a convenient metal knob for removing the charge. If both comb and rubber are insulated and connected together by a metal wire, a continuous passage of +ve electricity will take place along the wire from the comb to the rubber—we say that *a current of electricity* would then pass through the wire.

The cylinder machine only works satisfactorily in a dry atmosphere and is consequently not altogether reliable; for this reason the modern influence machine has almost entirely superseded it.

The Wimshurst Influence Machine (Fig. 141).—Although numerous types of influence machines have been devised, yet the Wimshurst machine is so frequently adopted in this country that a description of it alone will suffice to exemplify the class to which it belongs. It consists of two circular plates of varnished glass, placed as close together as possible, and geared so as to rotate in opposite directions. On the outer surface of each plate are fastened an even number of thin metal sectors, which serve both as *inductors* and *carriers*. Across the front is fixed a diagonal conductor terminating in metal brushes which touch the sectors as they pass; a similar diagonal conductor is fixed across the back plate, but sloping in the opposite direction. The insulated collecting combs are placed at opposite ends of the horizontal diameter, and each comb has teeth projecting towards the sectors on both front and back plates. Two Leyden jars are often supported on the base-board of the machine, with their knobs connected to the collecting-combs by movable wires. The combs are supplied with adjustable discharging knobs which are placed above the machine.

The action of the machine is best explained by means of

a diagram (Fig. 142), in which the two plates are represented as though they were two cylinders of glass rotating opposite ways as shown by the arrows. The neutralising brushes are represented by n_1n_2 and n_3n_4. In order to start the machine it is sufficient if one of the sectors has a slightly

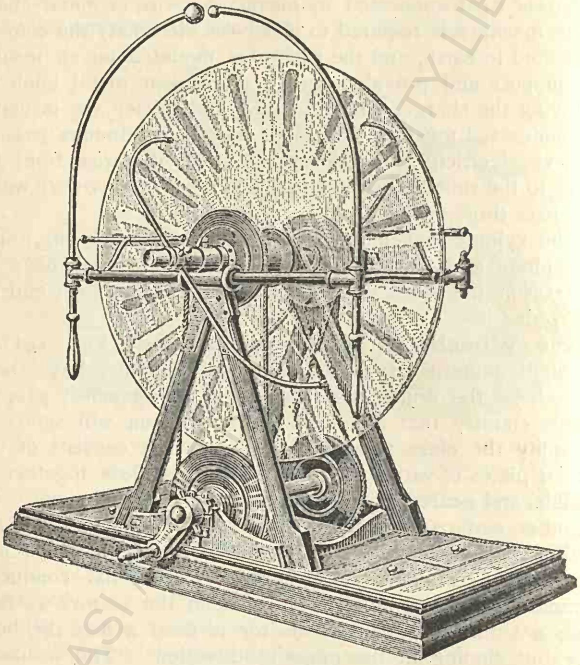


FIG. 141.—Wimshurst machine.

different potential to that of the others; as a rule this is the case, and the machine is then *self-starting*. Imagine that one of the back sectors at the top of the diagram has a slight +ve charge. When it comes opposite the brush n_1 it will act inductively on the sector touching n_1, giving to it a slight −ve charge, and simultaneously giving a +ve charge to the

sector touching n_2. These sectors, with their induced charges, leave the brushes and rotate into positions opposite the brushes n_3 and n_4; the sectors touching n_3 and n_4 will now receive induced +ve and −ve charges respectively, which they will retain after leaving the brushes. Thus, after one or two revolutions, all sectors approaching the left-hand comb will

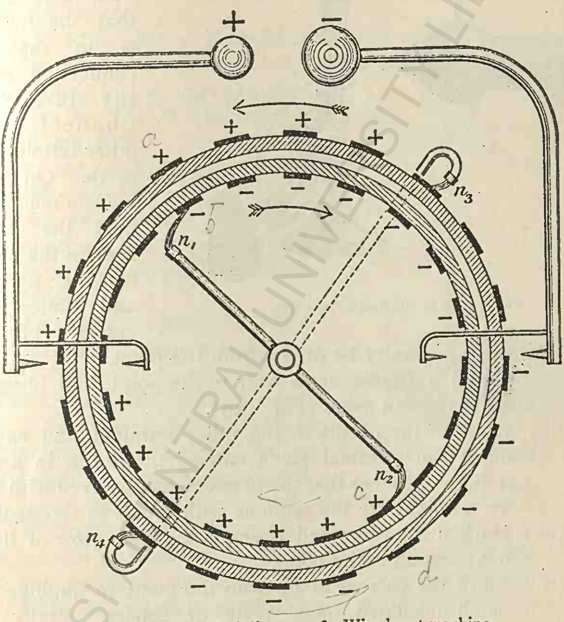


FIG. 142.—Theoretical diagram of a Wimshurst machine.

have +ve charges, and all sectors approaching the right-hand comb will have −ve charges. The sectors will be neutralised by the combs, the knobs connected to which will acquire +ve and −ve charges respectively.

If the machine is found not to be self-starting it is sufficient to hold a piece of electrified vulcanite near to the front plate opposite the brush n_3.

Action of Points. EXPT. 121.—(i.) Attach a sewing-needle or a piece of copper wire with sharpened end to the terminal of a Wimshurst machine by means of soft wax, taking care that the needle is in metallic connection with the terminal. Connect the other terminal to earth. On turning the machine, hold the hand near to the point of the needle, and notice the current of air which appears to be driven from the point.

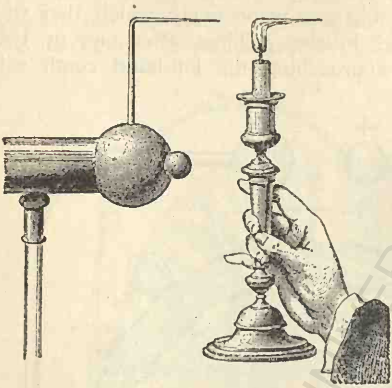


FIG. 143.—To illustrate Expt. 121.

Hold a candle flame near to the point, and observe how it is blown aside (Fig. 143).

(ii.) Transfer the needle to the other terminal, and earth-connect the terminal which carried the needle in Expt. 121 (i.). Observe that the phenomena observed with the − ve terminal are the same as with the + ve terminal.[1]

(iii.) Darken the room and observe the dull glow of light which surrounds the point.

(iv.) Allow the current of air from the point to impinge on a small insulated metal plate or sphere. Verify by means of an electroscope that the plate is charged with the same kind of electricity as that of the terminal to which the point is attached. Verify this statement by transferring the needle to the other terminal and testing the charge acquired by the metal plate. Evidently the stream of air which is repelled from the point is electrically charged.

We know that the surface-density on the pointed end of an

[1] See footnote, p. 219.

irregularly-shaped conductor is great (see p. 178). In Expt. 121 the surface-density at the point of the needle is so great that the air in contact with the point becomes charged with similar electrification, and is forcibly repelled away from the needle. This action continues until the conductor is discharged. Since electrical forces are mutual, then, if the point is free to move it should move in the *opposite* direction to that of the air current.

EXPT. 122.—Fix a **Hamilton's Mill** (Fig. 144) to the terminal of the Wimshurst, and observe how the wheel rotates in the opposite direction to that of the repelled air-currents.

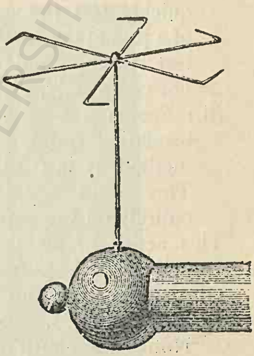


FIG. 144.—Hamilton's Mill.

EXPT. 123.—Fix small lumps of soft wax or sealing-wax on the end of the needle, and observe that the discharge from the point no longer takes place.

If the needle is charged *by induction* the same phenomenon of discharge is observed.

EXPT. 124.—(i.) Hold a needle in the hand, with its point towards the terminal of the machine. Interpose a candle flame between them, and observe how the flame is blown away from the point.

(ii.) Hold an insulated metal plate between the point and the terminal, and verify that the plate is now charged with the opposite electrification to that which is found on the terminal.

This experiment explains the action of *lightning conductors.* During a thunderstorm the clouds are electrically charged and induce an opposite charge on the earth's surface immediately beneath the cloud; if the potential difference is sufficiently great a spark discharge (in the form of *lightning*) takes place between the cloud and any conductor projecting above the earth's surface. By fixing an earth-connected metal point (*i.e.* a lightning conductor) over the building to be protected,

any + ly charged cloud will cause an induced − ve charge on the metal point, resulting in the partial or complete neutralisation of the cloud's charge.

Electrostatic apparatus should be free from sharp points and edges.—From these experimental results we should anticipate that a charged insulated conductor would be unable to retain its charge if any portion of its surface is pointed.

EXPT. 125.—(i.) Fix a needle to the surface of a large insulated sphere. Charge it from an electrophorus, and quickly test the surface-density of its charge by means of a proof plane and electroscope. After a few moments, test it again, and observe how the sphere is nearly, if not completely, discharged.

(ii.) Fasten a needle *inside* a hollow tin, place it on an insulating stand, and charge it. Observe by the same method as in (i.) that the tin does not lose its charge. This result would be expected, since the charge is entirely on the outer surface of the tin.

This action of points explains why it is necessary to avoid sharp points in all electrostatic apparatus.

Character of the Discharge from an Electrical Machine. I. Spark Discharge. EXPT. 126.—(i.) Notice the sharp intermittent sparks which pass almost in a straight line between the knobs of the machine. Separate the knobs still farther apart, and notice that the sparks are less frequent and trace out a zigzag path (Fig. 145).

The diminished frequency of the sparks with increased distance of the knobs apart is due to the fact that a greater difference of potential is necessary in order to overcome the dielectric strength of the air, and a greater interval of time is required to charge the knobs to the required potential. The discharge always follows the path of least resistance, and dust particles floating in the air are sufficient to divert the discharge from a straight path into a variable and zigzag path.

(ii.) Connect the two Leyden jars to the terminals of the machine, and notice that the sparks are less frequent but far more violent than before. The *capacity* of the knobs is now considerably increased by being connected to

the Leyden jars, and a far greater quantity of electricity must be collected in order to raise the potential of the knobs to a sufficient degree to cause a discharge between the knobs. *Carefully bring the knobs together before completing the experiment.*

(iii.) Attach a few small pieces of gummed paper to the surface of one of the glass discs of the machine, as near to the edge as possible. Darken the room, and observe the scraps of paper when illuminated by successive

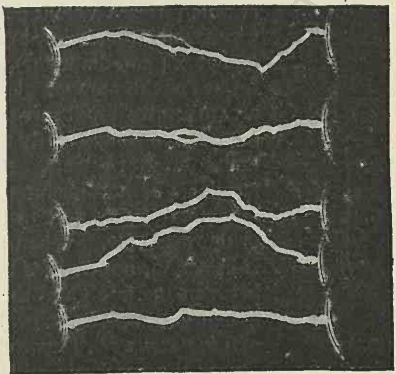


FIG. 145.—Consecutive spark discharges between the terminals of a Wimshurst machine. (From a photograph.)

sparks between the knobs. Notice that the paper seems to be absolutely at rest although they are really moving at a high speed. The duration of the spark is so brief that the discs do not move appreciably during the passage of a spark discharge.

Influence of Atmospheric Pressure on the Spark Discharge.—The character of the spark discharge largely depends upon the atmospheric pressure, and becomes considerably modified when the air between the discharging knobs is partially rarefied.

EXPT. 127.—Select a length of clean glass tubing about 50 cms. long and 2 cms. internal diameter. Contract

the lower end in a blowpipe flame, and attach to it a length of thick-walled rubber tubing. Fasten a small glass reservoir to the other end of the rubber tubing (Fig. 146). Fix the apparatus vertically in adjustable clamps. Pour clean mercury into the reservoir until it is nearly full. Slowly raise the reservoir until the glass tube is full of mercury. Close the upper end of the tube with a rubber stopper through the centre of which passes a stout brass or copper wire terminating below in a metal knob (about 0.5 cm. diameter), and coat the surface of the stopper with melted soft wax to render it quite air-tight. Lower the reservoir sufficiently to expose the metal knob to view. Connect the terminals of a Wimshurst machine to the metal knob, and to the mercury in the reservoir. When the machine is in action, notice that the discharge between the knob and the top of the mercury column has now the character of *a luminous glow* instead of a spark. Lower the reservoir still further, and notice that the discharge readily traverses a much longer distance than could be obtained if the air were not rarefied.

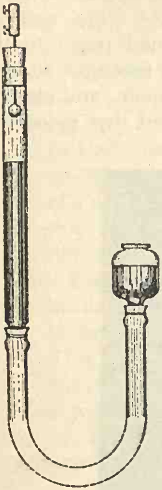


Fig. 146.—To illustrate Expt. 127.

All gases are bad conductors at ordinary pressure, but they become fairly good conductors when rarefied to an extreme degree. Moreover, the colour of the luminous discharge depends upon the gas which is present; each gas gives a characteristic colour which enables the phenomenon to be of great service in chemical analysis and other branches of scientific work.

Penetrative Power of the Spark Discharge.—The spark discharge has considerable penetrative power, and is capable of piercing holes through solid dielectrics in the same manner as found in the case of the discharge from a Leyden jar battery (Expt. 117).

EXPT. 128.—Hold a sheet of cardboard between the discharging knobs, and observe that each spark pierces a small hole through the cardboard; notice also that each hole appears to have a slight burr on both sides, as though the discharge had simultaneously passed in both directions.[1]

II. **Brush Discharge.**—This is obtained when the machine is worked vigorously, but with the knobs too far apart to

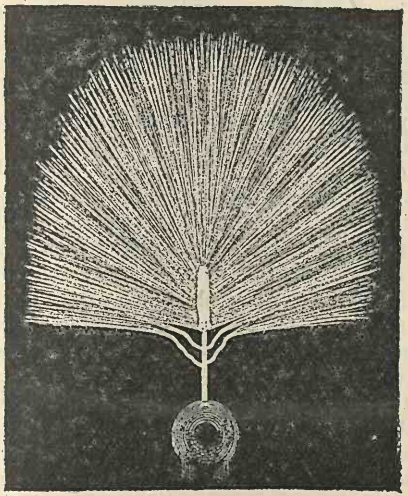


FIG. 147.—Brush discharge.

discharge by sparks. Fig. 147 represents a brush discharge obtained from a large machine.

EXPT. 129.—Connect one terminal of the machine to earth. Darken the room, and observe the knob of the insulated terminal. The effect is improved if a metal plate is held in the hand a short distance away from the knob.

[1] This experiment, and also Expt. 121 (ii.), are difficult to explain on the assumption that electricity is of one kind only, and the results suggest that Negative Electricity is a reality and distinct from the so-called Positive Electricity.

Notice the slight hissing sound which accompanies the discharge.

III. **Glow Discharge.**—This form of discharge is always observed when the discharged terminal is a sharp point. Its character has already been observed in Expt. 121 (iii.).

IV. **Discharge through Conductors.**—We see that the electric field of force between the terminals of a Wimshurst machine when in action may be destroyed rapidly by means of the spark discharge. A sequence of sparks will be accompanied by the equally rapid destruction and remaking of the electric field of force. The energy used up in this process is derived from the mechanical work done in turning the machine.

The field of force may also be destroyed by connecting the terminals together by means of a conductor. If a good conductor (such as copper wire) is used the field is almost instantaneously destroyed even before it acquires any considerable intensity. In fact, we have two opposing tendencies, (i.) the machine tending to create a field of force, and (ii.) the conductor tending to destroy it, with the result that there is a steady "flow" of electricity along the wire, which continues so long as any potential difference is maintained between the ends of the conductor. A steady "flow" of electricity has already been observed in the discharge through rarefied air (which is a conductor); in this case the "flow" is *visible*.

When the machine is in action there will be a gradual fall of potential between consecutive points of the wire, and the end in contact with the +ve terminal will have the highest potential. But copper is such a good conductor that the charges will not be able to accumulate in the terminals sufficiently to make the potential differences at all great. If a poor conductor, such as string or cotton, is used instead of copper, the discharge will be sufficiently slow to enable the machine to maintain a considerable potential difference between the terminals. The potential at various points along the string might be compared by connecting the points momentarily with a gold-leaf electroscope and observing the divergence of the leaves, but this instrument is too sensitive for such high potentials. The experiment may be more satisfactorily conducted by using several pairs of pith-balls

suspended by cotton threads from various points of the string; the degree of repulsion of the pith-balls will indicate the potential of that point of the string to which they are attached.

EXPT. 130.—Stretch a piece of thin string AE (1 metre long) between two vertical glass rods (40 cms. high). Connect the ends of the string to the terminals of a Wimshurst machine by means of copper wires. Suspend five pairs of pith-balls (on cotton threads) from equi-

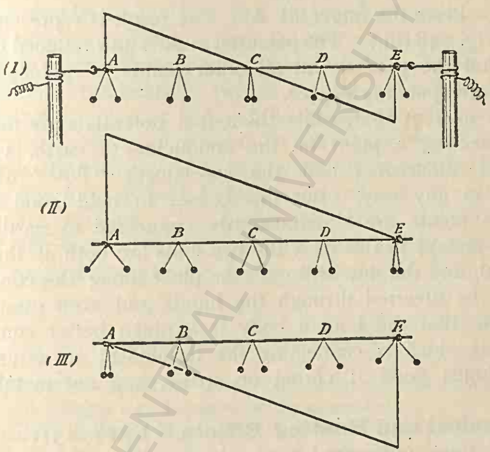


FIG. 148.—To illustrate Expt. 130.

distant points of the string. When the machine is in action notice how the greatest divergence is at A and E, less at B and D, and *nil* at C (Fig. 148, i.). Verify that the pith-balls at A are charged +ly by bringing near to them the charged plate of an electrophorus, and that the pith-balls at E are −ly charged by holding near to them an electrified rod of sealing-wax. The sloping line indicates the gradual fall of potential along the string. Place the finger on the string at C. The divergence of the pith-balls is in no case altered, since C is already at zero potential.

Place the finger at E. The pith-balls at E collapse, those at C now diverge, and the divergences at A and B increase. This would be anticipated from the change in position of the potential line (Fig. 148, ii.). The potential at E has been raised to zero, and the potential at all other points will be raised to a corresponding degree, since the machine will maintain the same *potential difference* between the terminals quite independently of the actual values of the potentials.

Place the finger at A. The result is represented in Fig. 148 (iii.). The potential at A is now reduced to zero, and the potential at all other points is reduced to a corresponding degree.

It is evident that, while the actual potentials are modified by connecting a point on the conductor to earth, yet the potential differences and the consequent "flow" are not altered in any way. But this ceases to hold good if *two* different points are simultaneously connected to earth (*e.g.* the two ends); in this case the two ends are both at the *same* potential, and the flow will not take place along the conductor but will be diverted through the hands and arms (assuming, of course, that the human body is a much better conductor than that which is connecting the terminals; an assumption which holds good if cotton or string, and not metals, are used).

Chemical and Heating Effects. EXPT. 131.—Obtain a stream of sparks between the terminals of the machine. After a few moments it will be possible to detect the characteristic smell of **Ozone**, which is a chemically modified form of oxygen. The oxygen of the air undergoes a *chemical change*, and is converted into the denser and more chemically active ozone.

EXPT. 132.—Place a strip of wet *starch paper*[1] on a sheet of glass lying on the table. Place the free ends of two wires, which are connected to the terminals of the machine, in contact with the paper and about 2 cms. apart. After turning the machine for a few moments,

[1] Starch paper is made by dipping strips of white blotting-paper in a hot solution of starch to which two or three small crystals of potassium iodide have been added.

observe the deep-blue patch which appears on the paper where one of the wires touches the paper.

The *heating effect* of an electric discharge has already been exemplified in Expt. 117 (ii. and iii.).

Many of the experiments described in this chapter convey the idea that an electric machine is a means whereby mechanical energy (spent in turning the machine) is converted into other forms of energy (currents of electricity, heat, and chemical action). In fact we find, in several of the experiments, examples of the fact that the various forms of energy are mutually convertible. Thus the mechanical work done in turning an electrical machine is partly used up in overcoming the friction of the bearings (which become heated), and partly in creating an electric field of force between the terminals. When the latter is destroyed by the passage of a spark discharge, the energy which was stored up in the field finally assumes the form of heat, light, and sound. If the discharge takes place through a conductor we should find, with the aid of sufficiently delicate apparatus, that all the mechanical energy originally expended finally assumes the form of heat energy.

Chief Points of Chapter XIV

An Electrical Machine is any mechanism by which considerable electrostatic charges may be conveniently generated.

The Glass Cylinder Machine is an example of the earliest type of electrical machine. Its action is based upon the electrification of bodies by friction.

The Wimshurst Influence Machine is an example of the modern type of electrical machine. Its action is based upon the phenomena of electrostatic induction.

Action of Points.—If any portion of the exterior of an insulated conductor terminates in a sharp point, the density of a charge given to the conductor becomes great on the surface of the point. The air in contact with the point acquires a portion of the charge and is forcibly repelled away; this action continues until the body is completely discharged. If the point is situated inside a hollow conductor the discharging action does not take place.

Character of an Electric Discharge. 1. *Spark Discharge.*—This is practically instantaneous. It has considerable penetrative power. Its character is changed to a continuous luminous glow when the air is considerably rarefied.

2. *Brush Discharge.*—This is observed when the terminals of a machine are too far apart for the spark discharge to take place.

3. *Glow Discharge.*—This is observed when the discharge takes place from the end of a sharp-pointed conductor.

4. *Discharge through Conductors.* — This is a steady invisible "flow" continually tending to destroy the field of force between the two charged bodies which are connected by the conductor.

Questions on Chapter XIV

1. Explain the difference between a frictional machine and an influence (or induction) machine. Under which heading would the electrophorus be classed?

2. Explain why the points on the prime conductor of an electrical machine are necessary; also why the rubbers are earth-connected.

3. When the handle of an ordinary frictional machine is turned, sparks can be drawn from the prime conductor. Explain carefully how the prime conductor becomes charged with electricity. (1888.)

4. How could you show that electricity gathers most at points and corners of a conductor? Give two practical applications of this property. (C. U. L. S. 1898.)

5. An orange, into which a sewing-needle has been stuck, point outwards, is suspended by a dry silk thread. A charged body is brought near to it (1) opposite the point of the needle, (2) opposite the side remote from the needle. State and explain the electrical effect in each case. (1887.)

6. A sharp point attached to a conductor A is held near an insulated charged conductor B. What will be the effect on B if A is (1) insulated, (2) uninsulated? (1888.)

7. A large Leyden jar, the outer coating of which is earth-connected, is charged. If you wish to discharge it with the electric tongs, which coating should you touch first with the tongs, and why?

8. A sharp point is attached to the interior of a hollow metallic sphere. Describe and explain the action of the point (1) when the sphere is electrified, (2) when one end of a brass rod, the other end of which is held in the hand, is cautiously introduced into the sphere through a small hole so as not to touch the sphere and is brought near to the point. (1898.)

9. Two gold-leaf electroscopes, similar in all respects except that a needle projects from the cap of one of them, are placed at equal distances from an electrical machine. When the machine is worked both pairs of leaves diverge. When it ceases to work one pair of leaves collapses rather quickly and the other pair very slowly. Explain this difference in their behaviour. (1892.)

10. A hemispherical metal bowl, to which a short metal point is attached, is charged with electricity. What difference, if any, in the rate of loss of electricity will there be according as the point is fastened to the concave or the convex side of the bowl? (1893.)

11. Describe a simple experiment which will imitate on a small scale the action of a lightning-conductor.

12. Explain the difference in character between an electrical discharge through air when at ordinary pressure and when the air is rarefied.

13. Two large insulated spheres are joined together by a long piece of cotton, and the spheres are joined by separate wires to the terminals of a Wimshurst machine in action. Draw a potential diagram of the cotton thread, and explain what the effect would be of touching various points of the thread with the finger.

CHAPTER XV

CONTACT ELECTRICITY

Apparatus required.—Condensing electroscope. Gold-leaf electroscope. Insulated discs of copper and zinc. Dilute sulphuric acid. Filter or blotting-paper. Sheet of glass.

Preliminary. — Hitherto we have obtained opposite electrifications on the surfaces of two different bodies by rubbing them together. It does not follow that the electrification obtained is the equivalent of the work done in *rubbing* the bodies together, since, however much the bodies are rubbed together beyond a certain limit, we do not find an equivalent increase in the degree of electrification. The energy which a body possesses after being electrified in this manner is rather the equivalent of the mechanical work done in *separating* the oppositely charged surfaces (*i.e.* in stretching the lines of force which connect the opposite charges). The actual rubbing is certainly a *technical* advantage, since it increases the extent of the surfaces of contact of the two bodies. If this reasoning is correct, then the rubbing might be completely dispensed with, and the mere contact of the two bodies should suffice to bring about the opposite electrification of the two surfaces, though to a much smaller degree than if the contact is aided by rubbing.

Any experiments on this question require far more delicate appliances and more manipulative care than have been necessary for previous experiments. A condensing electroscope, as described in the next section, is absolutely necessary.

The Condensing Electroscope.—The action of the condensing electroscope depends upon the principle that if the plates of a simple condenser are charged to a slight differ-

ence of potential, and the plates are then separated to a considerable distance apart, the difference of potential becomes highly magnified owing to the diminished capacity of the condenser. The following is a simple form of apparatus which can be made at a small cost. A and B (Fig. 149) are two discs of stout brass (about 20 cms. diameter) the surfaces of which have been turned in a lathe. The lower disc is sup-

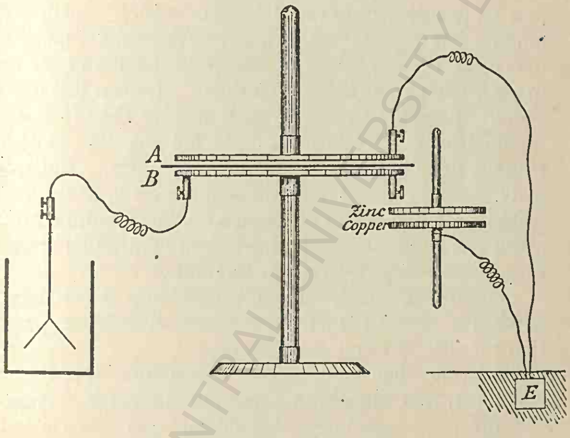


FIG. 149.—A condensing electroscope.

ported horizontally on a vertical rod of unpolished vulcanite, which is mounted on a suitable base. The upper disc is also supplied with a vulcanite handle. Binding-screws are fixed to the outer surface of each plate, as shown. Both plates are lacquered (or varnished), *but not the binding-screws.* The plate B is connected by a wire to a gold-leaf electroscope, the disc of which has been removed and replaced by a binding-screw; the plate A is earth-connected. When in use, the plates are separated from each other by a thin sheet of paraffined paper, so as to render the insulation perfect. If a slight charge is given to B no divergence of the leaves will be observed; but if A is now raised, the potential of B will be considerably raised and the leaves will diverge.

Volta's Fundamental Experiment. EXPT. 133.—(i.) Obtain two flat discs of zinc and copper (about 5 cms. diameter). Each disc must have an insulating handle of vulcanite, and the metal surfaces must be perfectly flat and clean. Connect the copper disc to earth. Holding each disc by its handle, bring them into contact, with the zinc disc a few cms. below one of the binding-screws of the plate B (Fig. 149). Keeping the copper disc in position, raise the zinc disc until it touches the binding-screw, and then bring it back into contact with the copper disc. Take care not to tilt the discs relatively to each other when separating them. Repeat this fifteen times. Raise the plate A, and observe the divergence of the leaves. Replace A, and continue the charging with the zinc disc for another fifteen contacts. Raise the plate A, and observe that the divergence is about twice what it was before. The process may be continued until about one hundred contacts have been made, an increased divergence being observed at intervals.

Remove A completely, and bring any +ly charged conductor near to B; the increased divergence proves that the disc B has a +ve charge.

(ii.) Discharge the condenser. Invert the copper and zinc discs, and connect the zinc disc to earth. Repeat the previous experiment by raising and lowering the copper disc. The plate B will become charged, but its charge will be −ve instead of +ve.

Hence, *when discs of copper and zinc are placed in contact, a difference of potential is set up which produces charges on the discs which can be detected by means of a condensing electroscope.* The metals are good conductors, and therefore the tendency of electricity to flow from the metal at a higher potential must be checked by an opposing difference of potential which is set up on the surfaces of contact.

Volta's Laws.—Expt. 133 is a repetition of one which was first carried out by Volta, an Italian physicist, in the year 1801. He repeated the experiment, using discs of various metals, and from the results obtained he deduced the following laws:—

(i.) When two metals are placed in contact, a difference of potential is set up between them, which depends upon the nature and temperature of the surfaces.

(ii.) A list of elements may be drawn up such that any one is + ve when touched by any one following, and − ve when touched by any one preceding it.

+ ve Zinc, Lead, Tin, Bismuth, Antimony, Iron, Copper, Silver, Carbon − ve.

Much additional information regarding this phenomenon has been obtained since Volta's time, and one remarkable fact is that two discs of the same metal will acquire different charges when in contact, *if* their surfaces are of different character, *e.g.* two plates of zinc, one burnished and the other rubbed with emery cloth, will exhibit a similar phenomenon.[1]

The true origin of this difference of potential due to contact is a question which is still under discussion. One theory states that the effect is purely a *physical* one, called into existence at the moment of contact; another theory attributes the phenomenon to *chemical* action of the surrounding medium. The two theories can scarcely be discussed in an elementary text-book.[2]

Contact Effects between Metals and Liquids.—Effects similar to those obtained between two metals can also be observed between metals and liquids (*e.g.* water, brine, and acids). But the liquids cannot be tabulated in Volta's second law with the metals, since the order of the metals is not the same for each liquid; moreover, the magnitude of the effect varies with the concentration of the liquid. With dilute sulphuric acid, all metals become − ly charged except platinum, gold, and silver (which become + ly charged). Of all the metals, zinc acquires the greatest − ve charge.

EXPT. 134.—Instead of the zinc and copper discs described in Expt. 133, use an insulated disc of sheet-zinc and a circular piece of blotting-paper moistened with dilute sulphuric acid. Lay the blotting-paper on a sheet of glass which is lying on the table, touch the paper with

[1] Compare Expt. 76.

[2] See Prof. S. P. Thompson's *Elementary Lessons in Magnetism and Electricity*.

the zinc disc, and raise the disc into contact with the binding-screw attached to plate B. Touch the paper so as to reduce its potential to zero again, and repeat the contact with the zinc disc. Continue this process about twenty times. Raise the condenser-plate A and observe the divergence of the leaves. Verify that the divergence is due to a − ve charge.

An Electric Current generated by Contact Electricity.—Imagine that the zinc and copper discs, used in Expt. 133, are now experimented with in the manner shown in Fig. 150. After separating the discs let them simultaneously touch two insulated metal knobs which are connected together by a wire. The upper knob acquires a + ve charge, and the lower knob acquires a − ve charge. Electricity flows along the wire, and the opposite charges neutralise each other. Again bring the disc together and separate them as before. In this manner, a succession of momentary discharges will be made to pass down the wire. If the movement of the discs is obtained by some mechanical contrivance so that the process is very rapidly repeated, an approximately steady stream of electricity will be obtained in the wire—in fact, we should have what is termed **a current of electricity**. The energy of the current, which is used up in heating the wire, would be derived from the *mechanical work* which is necessary in order to separate the oppositely charged discs. Such a method is not convenient in practice, but we may still make use of some other form of energy, *e.g. heat*, or *chemical action*. If heat is the source of the energy, the current which is obtained is termed a **thermo-electric current**;[1] if chemical action is the source of energy, the current which is obtained is termed a **voltaic current**. The latter forms the subject of the next chapter.

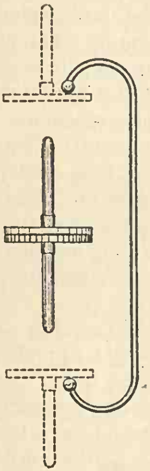


FIG. 150.

[1] See Prof. S. P. Thompson's *Elementary Lessons in Magnetism and Electricity*.

Chief Points of Chapter XV

Contact Electricity.—In order that two different bodies may acquire opposite charges it is only necessary to bring them *into contact* with each other, an appreciable effect being obtained even without any actual rubbing of the bodies together. The effect may be readily observed by using insulated discs of copper and zinc.

A Condensing Electroscope is required in order to perceive these effects.

Volta's Laws.—1. *When two metals are placed in contact, a difference of potential is set up between them, which depends upon the nature and temperature of the surfaces.*

2. *A list of elements may be drawn up such that any one is +ve when touched by any one following, and –ve when touched by any one preceding it.*

Contact Effects between Metals and Liquids.—Similar phenomena may be observed between metals and liquids, for example zinc and sulphuric acid. All metals acquire a –ve charge when brought into contact with sulphuric acid, and zinc acquires a greater –ve charge than other metals.

Questions on Chapter XV

1. Explain the action of a condensing electroscope.

2. Describe an experimental method for showing that a difference of potential is set up between pieces of zinc and copper when brought into contact with each other. State the precautions which must be taken in order to carry out the experiment successfully.

3. A copper funnel is clamped in a vertical position, and zinc filings are allowed to fall through the funnel on to an insulated zinc plate which is connected to a gold-leaf electroscope. State what happens.

4. If you are supplied with three metal discs, of copper, iron, and zinc, each supported on an insulating handle, describe how you would proceed to find out by experiment which pair of discs will give the greatest potential difference when brought into contact.

PART III

VOLTAIC ELECTRICITY

CHAPTER XVI

CHEMICAL ACTION, AND THE SIMPLE VOLTAIC CELL

Apparatus required.—Zinc-sheet (commercial, and also pure). Copper-sheet and turnings. Iron filings. Charcoal. Mercury. Dilute sulphuric acid. Test-tubes. A simple voltaic cell. A battery of simple cells, and a condensing electroscope. Compass-needle, and a magnetised knitting-needle. Copper wire, and binding-screws. Permanganate of potash. Bichromate of potash.

Chemical Action.—The generation of electricity by voltaic methods, and also many of the phenomena connected with it, are so dependent upon chemical changes that it is essential for the student to have a clear conception of what we mean by the term *chemical action*. All the phenomena which we have hitherto considered may be termed *physical*, and not *chemical*. For example, when a steel bar is magnetised it acquires new physical properties, but the substance of the steel itself undergoes no change, and we say that the steel has undergone a *physical change*. But if the steel is allowed to rust it becomes changed into a substance which is entirely

different from the original steel—we say that the steel has undergone a *chemical change*. Such changes as this are due to *chemical action*. **Chemical action results in the change of substances from their original form into new substances with new properties.** A simple experiment will explain more clearly the character of chemical action.

EXPT. 135.—Drop a small strip of commercial zinc into a test-tube containing dilute sulphuric acid (1 in 8). Notice that bubbles of a gas are given off from the surface of the zinc. Close the end of the test-tube with the thumb for a few moments, so as to prevent the gas from escaping. Remove the thumb and hold the open end of the tube at the side of a gas flame. The gas in the test-tube burns with a dull blue flame. The gas obtained by this means is called *hydrogen*. At the same time observe that the zinc gradually disappears.

The zinc decomposes the acid, and liberates hydrogen, which is one of the constituents of the acid. Each molecule of the acid contains atoms of hydrogen, sulphur, and oxygen, which are chemically combined in definite proportions, viz. 2 atoms of hydrogen, 1 atom of sulphur, and 4 atoms of oxygen. The chemical symbol for sulphuric acid is therefore H_2SO_4.[1]

Expt. 135 may be expressed thus :—

Zinc added to sulphuric acid gives hydrogen and sulphate of zinc.

Or, the same fact may be expressed in chemical symbols :—

$$Zn + H_2SO_4 = H_2 + ZnSO_4.$$

It will be seen, by subsequent experiments, how this chemical change may be utilised in the generation of electricity.

[1] Frequent use will be made of the recognised chemical symbols of various substances. The following list includes all that will be used in this book :—

H = Hydrogen	Zn = Zinc	C = Carbon
O = Oxygen	Cu = Copper	S = Sulphur
N = Nitrogen	Pt = Platinum	Mg = Magnesium.

The burning of the hydrogen, in Expt. 135, is an example of a very characteristic kind of chemical change. The hydrogen chemically combines with the oxygen in the air (which may be regarded as a mixture of the gases oxygen and nitrogen).

In burning, **hydrogen** combines with **oxygen** to form **water**; or,

$$H_2 + O = H_2O.$$

Many other substances are capable of combining chemically with oxygen, and we say that the substances become *oxidised* by such chemical changes. For example, the metal magnesium will burn readily in air.

In burning, **magnesium** combines with **oxygen** of the air to form **oxide of magnesium.**

$$Mg + O = MgO.$$

Or, magnesium in combining with the oxygen of the air is **oxidised** to oxide of magnesium. Zinc will not burn so readily, but it may be made to do so if heated to a sufficiently high temperature.

EXPT. 136.—Cut a very narrow strip of sheet-zinc. Hold the end of the strip in the flame of a mouth blow-pipe (or foot blow-pipe, if available). Notice how the zinc burns with a bright blue-green flame, and becomes changed to a white powder. This powder is *oxide of zinc*, and has been formed by the chemical combination of zinc and oxygen.

In burning, **zinc** combines with **oxygen** to form **oxide of zinc**; or,

$$Zn + O = ZnO.$$

The Theory of the Simple Voltaic Cell.—We know that when zinc is in contact with dilute sulphuric acid that the zinc is at a lower potential than the acid (p. 229); so also when copper is in contact with the acid it is at a lower potential than the acid, but not so much so as zinc. If pieces of both metals are dipped into a vessel containing the dilute acid (Fig. 151, i.), and if the zinc plate is connected to earth by means of a copper wire, we may indicate the relative potentials of the various parts by means of a diagram (Fig. 151, ii.). The

copper wire is at zero potential, and the potentials of the zinc, sulphuric acid, and copper plate are represented by the thick horizontal lines. The difference of potential between the copper plate and the copper wire is represented by the height of the dotted line E above the zero line. This diagram may be simplified, for the sake of clearness, by combining the first two steps in the potential ladder, and so giving to it the form shown in Fig. 151 (iii.). It is difficult to detect this small difference of potential by means of a condensing electroscope, but the difference may be multiplied by placing several such cells in a row, and connecting the copper plate of one cell to the zinc plate of the next, and so on. Fig. 152 represents the potential conditions for two such cells connected together. The difference of potential between the copper plate and wire at the opposite ends of the series is thus doubled (Fig. 152). If thirty cells are connected together in this manner the difference of potential between the extreme ends will be thirty times as great as the difference between the plates of a small cell. This may be experimentally demonstrated with a battery of simple voltaic cells[1] and a condensing electroscope.

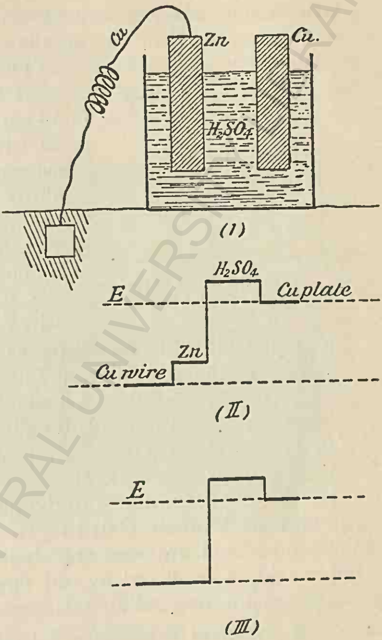


FIG. 151.—Potential diagram of a simple voltaic cell.

[1] A suitable form of battery may be constructed in the following

EXPT. 137.—Connect the zinc-plate of the first cell to earth, and attach a copper wire to the copper plate of the thirty-sixth cell. Wrap the free end of the latter wire round a rod of sealing-wax, which will serve as an insulating handle. Fit up the condensing electroscope as described on p. 227. Connect the condenser-plate A to earth, and touch the plate B with the free end of the copper wire connected to the thirty-sixth cell (supporting the wire by the sealing-wax handle). Raise the plate A, and observe the divergence of the leaves. Disconnect the wire from the thirty-sixth cell, and attach it to the copper plate of the twenty-fourth cell. Discharge the condenser, and touch the plate B with the wire as before. Raise A and observe the divergence; it will be about two-thirds the divergence observed when thirty-six cells were used. Repeat the experiment, using twelve (or even fewer) cells. The divergence obtained is evidently proportional to the number of cells used.

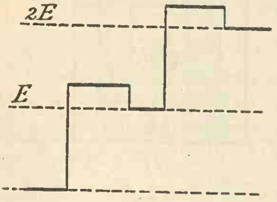


FIG. 152.—Potential diagram of two simple cells in series.

The Simple Voltaic Cell in Practice.—If the poles of a simple voltaic cell are connected together by a wire outside the dilute acid, +ve electricity will flow along the wire from the copper to the zinc. But it is found that the subsequent

manner :—Bore a row of twelve shallow holes ($\frac{1}{2}$ inch in diameter, and 1 inch apart) in a strip of wood (14 × 2 × 2 inches). Place in each hole a small test-tube or sample-tube (2 inches × $\frac{1}{2}$ inch). Cut twelve strips of sheet-copper ($1\frac{1}{2}$ inch × $\frac{1}{4}$ inch) and an equal number of sheet-zinc strips of the same size. Solder the ends of the copper strips to the zinc strips so as to make twelve separate zinc-copper strips. Bend each compound strip so that the copper dips into one tube and the zinc into the next tube. Nearly fill each tube with *very* dilute acid. To ensure perfect insulation it is advisable to paint the wooden stand with melted paraffin-wax. The arrangement now forms a series of twelve cells, and the potential difference between the extreme ends is twelve times as great as the difference between the plates of one cell. It is an advantage to have even a greater number of the cells connected together, by making two more complete sets of twelve cells similar to the set described above, and connecting the three sets so as to form a series of thirty-six cells (Fig. 153).

action differs from that observed when two insulated conductors, at different potentials, are connected by a wire. In the latter case the potentials of the two conductors are immediately equalised. In the case of the voltaic cell the potentials are not equalised although the charge continues to pass along the wire; the potential difference is maintained *by the chemical action of the zinc on the acid.* The force which serves to maintain the potential difference between the metal

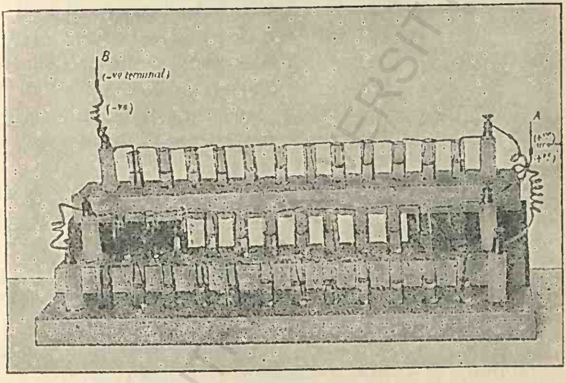


FIG. 153.—A battery of thirty-six simple cells.

plates is called the **Electro-motive Force** of the cell (usually written **E.M.F.**). Since the degree of potential difference between the plates is dependent upon the degree of E.M.F. inside the cell, it follows that the numerical value of either expresses at the same time the value of the other, and it is customary to refer to the potential difference of the metal plates as *the* E.M.F. *of the cell.* As long as the potential of the copper is maintained, a discharge of +ve electricity will pass along the wire, or, in other words, a *current of electricity* is obtained. The current will only cease when either all the zinc or all the acid has been used up.

How can this current be detected? EXPT. 138.—Cut two rectangular pieces of sheet-copper and sheet-zinc (10×4 cms.); solder a short piece of thick copper

wire to the upper edge of each. Fig. 154 represents a convenient method of supporting the plates in a beaker of dilute sulphuric acid. Connect the terminals by means of a fairly long thin copper wire. Place a compass-needle on the table and hold just over it a straight piece of the connecting wire, the wire being so adjusted that it lies in the magnetic meridian. Notice how the needle is deflected. This is a simple test for the presence of an electric current, the theory of which will be explained in a subsequent chapter. Since + ve electricity is passing to the zinc plate, either its potential must be raised to that of the copper plate or the current must pass out of the zinc as rapidly as it enters. Is a current also passing through the acid?

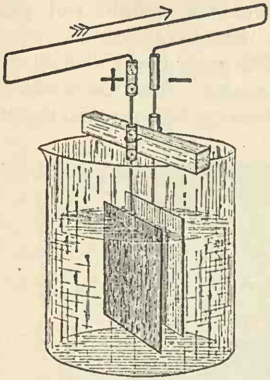


FIG. 154.—A simple voltaic cell.

EXPT. 139.—Remove the plates from the wooden support. Support a compass-needle just above the surface of the acid by means of a narrow copper bridge suspended from opposite sides of the beaker (Fig. 155). Connect the two plates together with a long thin wire. Adjust the bridge so that it is approximately at right angles to the magnetic meridian. Dip the two plates simultaneously into the acid and observe the deflection of the needle. Remove the plates, and notice that the deflection ceases. Reverse the position of the plates in the acid, and observe that the deflection is now in the opposite direction to that in the first case.

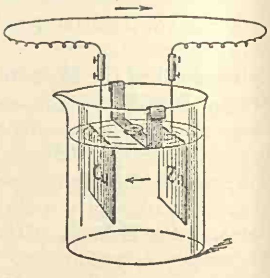


FIG. 155.—To illustrate Expt. 139.

Evidently a current is passing through the acid between the metal plates. Examine the cell more closely, and observe that bubbles of gas are escaping from the surfaces of both plates. Remove the connecting wire and observe that the bubbles have ceased to form on the surface of the copper, but that they continue to form on the surface of the zinc. Evidently the chemical action between the acid and the zinc continues, and is simply a repetition of Expt. 135. The zinc is being wasted, and the equivalent amount of chemical energy is being lost.

Local Action.—So far *commercial* zinc only has been used. Would *pure* zinc be acted upon by acid in the same way?

EXPT. 140.—Place a fragment of *pure* granulated zinc in a test-tube and add dilute sulphuric acid. No chemical action can be observed.

Can commercial zinc be so treated as to prevent this waste going on in the simple cell?

EXPT. 141.—Place a small piece of commercial zinc in a test-tube, add some dilute acid, and observe the rapid chemical action. Now add a *small* drop of mercury, and thoroughly shake the tube. The surface of the zinc soon becomes completely amalgamated by the mercury, and the chemical action ceases.

EXPT. 142.—Amalgamate the zinc plate used in Expt. 138, by dipping it into dilute sulphuric acid for a few moments in order to clean the surface, and then rubbing a drop of mercury over the surface with a piece of cotton wool or cloth. Connect up the cell as in Expt. 138, and observe that bubbles of gas no longer escape from the zinc, but that they continue to form on the surface of the copper.

Why does commercial zinc act in this way? From chemical analysis it is known that commercial zinc always contains a small quantity of impurities, chiefly iron and carbon.

EXPT. 143.—(i.) Add some dilute sulphuric acid to a fragment of *pure* zinc in a test-tube. No chemical action takes place. Add a few small pieces of copper turnings. Vigorous chemical action immediately pro-

ceeds. Notice that bubbles of gas are being liberated from the copper, *but not from the zinc*. The phenomenon is really a repetition of Expt. 138 on a small scale. What is the gas which is being given off? Close the end of the tube with the thumb for a few moments, and verify that it is the combustible gas hydrogen.

We really have, in this case, a simple voltaic cell. The connecting wire is dispensed with, since the copper and zinc are already connected together beneath the surface of the acid.

(ii.) Repeat Expt. (i.), but add a few iron filings instead of copper turnings. The phenomena observed are identical in both cases.

(iii.) Repeat Expt. (i.), adding some finely divided charcoal instead of iron or copper. Well shake the tube, and observe that the phenomena are again the same.

In each of these cases we have all that is necessary to form a simple voltaic cell. From the Voltaic Order (see p. 229), iron or carbon may be used instead of copper in the construction of a simple voltaic cell. Hence, when commercial zinc is dipped into dilute acid, each speck of iron and carbon on its surface will form a minute voltaic cell, which will eat away the surrounding zinc, and hydrogen will be liberated from the specks of iron or carbon. **This effect is known as Local Action.** *Amalgamation prevents local action*, because the mercury will dissolve zinc but will not dissolve iron and carbon; the film of mercury on the surface therefore supplies pure zinc to the dilute acid, but serves as a protecting layer to the particles of iron and carbon, which would cause local action if allowed to come into contact with the acid.

Polarisation.—Each small portion of the copper plate to which a bubble of hydrogen adheres is protected from the acid, and thereby the effective area of the copper plate is reduced. The accumulation of hydrogen is injurious for another reason. Hydrogen is readily oxidised (p. 234), and behaves, in this sense, similarly to zinc. If hydrogen were included in the Voltaic Order, it would be placed near to the zinc end, and if present in a voltaic cell it behaves somewhat similarly to a zinc plate and *tends* to send a current through

the acid *from the copper to the zinc.* In this manner the primary effect of the metal plates is reduced by the opposing tendency of the hydrogen. The current passing through the cell and the connecting wire is consequently reduced. *This effect, due to the hydrogen accumulating on the copper plate, is termed* **Polarisation of the cell.**

EXPT. 144.—Connect up a simple voltaic cell (Expt. 138) in series with a sensitive tangent galvanometer, a resistance box, and a plug key. Adjust the resistance until a suitable deflection is obtained, then break the circuit. Remove the copper plate, wash and *thoroughly dry* it, and replace it in the cell. Complete the circuit and read the deflection *as quickly as possible.* Take eight consecutive readings at 2-minute intervals. The previous drying of the copper plate is important.

Removal of the hydrogen by mechanical means is not convenient, but it is possible to prevent its accumulation by chemical means, *e.g.* by oxidising it. It cannot be burnt in the air in this case, but other substances besides air afford a supply of oxygen available for this purpose (*e.g.* permanganate of potash, manganese dioxide, or bichromate of potash). These substances contain much oxygen, which they readily give up when dissolved in water—they are termed *oxidising agents.*

EXPT. 145.—(i.) Add dilute sulphuric acid (1 in 40) to a fragment of commercial zinc in a test-tube. Observe the hydrogen being liberated. Add some strong solution of permanganate of potash, and observe how the liberation of hydrogen completely, or almost completely, ceases.

(ii.) Repeat Expt. (i.), but add some strong solution of bichromate of potash (instead of permanganate).

Allow these reactions to continue for half an hour, and observe how the characteristic colours of the permanganate and the bichromate are totally changed, showing thereby that they have undergone chemical change.

The permanganate of potash (or the bichromate of potash) loses oxygen, or is, as we say, **reduced**; the oxygen given up combines with the hydrogen and **oxidises** it. So that the

oxidation of the hydrogen is always accompanied by the reduction of the oxidiser. This experiment explains the chemical method of preventing polarisation which is used in some of the more important types of voltaic cells. Nitric acid (HNO_3) is also a strong oxidising agent, but it does not lend itself to the simple test described in Expt. 145, owing to the fact that it will vigorously attack the zinc.

Any chemical substance used for the purpose of preventing polarisation may be termed a **depolarising agent**.

Theory of the Chemical Changes in a Simple Cell.—The chemical changes which have been proved by experiment to take place

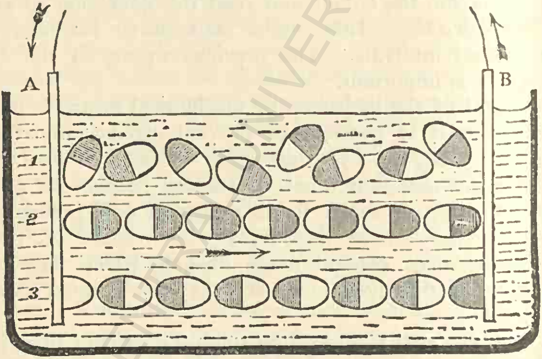


FIG. 156.—Grotthuss' theory of the simple cell.

in a simple cell are (i.) the gradual disappearance of the zinc, and (ii.) the liberation of hydrogen from the copper plate. The copper plate itself remains unaltered, how is it then that the hydrogen appears on the copper plate instead of on the zinc plate? One theory offered to explain this phenomenon states that the hydrogen is really set free at the zinc plate, but that, instead of accumulating in bubbles, it attacks the neighbouring molecules of sulphuric acid, displacing the hydrogen contained therein, which in its turn acts similarly on other neighbouring molecules; this conduct of the molecules proceeds through the successive layers of acid molecules until the copper plate is reached, when the hydrogen appears in the form of bubbles of gas.

This theory is represented diagrammatically in Fig. 156. The oval figures represent individual molecules of sulphuric acid; the

shaded portion represents the hydrogen in the molecule, and the unshaded portion the group of elements SO_4. The first row represents the higgledy-piggledy arrangement of molecules before the plates are introduced into the acid. The second row represents the linear arrangement of the molecules brought about by the introduction of the zinc and copper plates, and the consequent presence of electro-motive forces through the acid and between the plates. The third row shows the effect produced by joining the plates with a wire, zinc sulphate being formed at the zinc plate, and hydrogen set free at the copper plate.

CHIEF POINTS OF CHAPTER XVI

Chemical Action must be distinguished from **Physical Action.**

The Simple Voltaic Cell.—Its construction and principle of action. The potential difference between its terminals, and the increased potential difference obtained by connecting together several simple cells *in series.*

The Electro-motive Force (E.M.F.) in the cell gives rise to, and is measured by, *the potential difference* (P.D.) between its terminals. The two terms are usually regarded as synonymous.

A Current of Electricity traverses a wire which connects together the terminals of a simple voltaic cell. The current may be detected by observing the deflection of a compass-needle placed immediately above or below the wire. The current also traverses the liquid separating the two plates in the cell.

Local Action.—Due to impurities (*e.g.* iron and carbon) in the zinc. Prevented by amalgamating the surface of the zinc plate with mercury.

Polarisation causes a gradual diminution in the activity of a simple cell, and is due to hydrogen accumulating on the surface of the copper plate. It is prevented either by mechanically removing the hydrogen, or by oxidising it by means of nitric acid, or bichromate of potash, etc. (These substances are termed *depolarising agents.*)

QUESTIONS ON CHAPTER XVI

1. A plate of pure zinc, and a plate of copper, are dipped into dilute sulphuric acid, and then connected by copper wire. What changes take place in the plates, wire, and acid, when the circuit is complete? (Lond. Matric. 1890.)

2. With a battery made up of many cells how would you show that the electrical conditions of the terminals differ from each other, and that the difference is of the same kind as that of the prime conductor and rubber of an electrical machine in action? (1896.)

3. The terminals of an insulated battery consisting of a large number of cells touch the caps of two electroscopes. What are the effects upon the two sets of leaves, and what would be the further effects of touching one of the caps with the finger? (1898.)

4. A hundred Grove cells are arranged in series, and wires attached to their terminals are momentarily brought into contact with the inner and outer coatings of a Leyden jar. What result will follow if the operation of discharging the jar is afterwards performed? Give reasons for your answer. (1891.)

5. Explain the meaning of the statement that the electric current flows in a circuit. By what experiments would you illustrate its accuracy? (1898.)

6. When a current passes along the wire joining the terminals of a battery, does the current also pass through the battery? Give reasons for your answer. (1896.)

7. When a plate of zinc and a plate of platinum connected by a wire are both dipped into the same vessel of dilute sulphuric acid, an electric current passes along the wire. State and account for the effect of moving one of the plates into a separate vessel of acid. (1881.)

8. Explain the cause of *Local Action*, and state how it may be remedied.

9. Explain the cause of *Polarisation*, and describe the chief methods of preventing it.

CHAPTER XVII

VOLTAIC CELLS

Apparatus required.—Examples of the various forms of voltaic cells. A simple commutator.

Many modifications of the simple cell have been devised in which the chief differences are due to the method of preventing polarisation adopted in each case.

The Bichromate Cell.—In this cell potassium bichromate is used as a depolariser, and is mixed with the dilute sulphuric acid. Carbon plates are used instead of copper, since the latter would be attacked by the mixture of acid and bichromate. A simple form of the cell is shown in Fig. 170, in which a carbon plate is placed on each side of the zinc. The carbon plates are joined together at the top. The zinc plate is supported by a metal rod which slides through the lid of the cell in order that the zinc plate may be raised out of the liquid when the cell is not in use. A solution of suitable strength for this cell may be made by mixing together the following quantities by weight:—100 parts water, 10 parts bichromate of potash, 30 parts sulphuric acid; in order to keep the zinc plate amalgamated it is well to add 0.25 part of mercurous sulphate.

The Leclanché Cell.—In this cell, known by the name of the physicist who devised it, the materials are zinc, carbon, and a concentrated solution of ammonium chloride (sal-ammoniac). Manganese dioxide is used as a depolarising agent. The carbon plate (C, Fig. 157, ii.) is placed in the centre of a cylindrical porous pot which is closely packed with a mixture of carbon and manganese dioxide. The zinc

rod **Z** dips into the solution of sal-ammoniac contained in the glass jar **G**. When the cell is in action, ammonia and hydrogen are produced; the ammonia gas, being very soluble in water, does not tend to produce polarisation. The manganese dioxide is but a very slow oxidising agent, and the cell

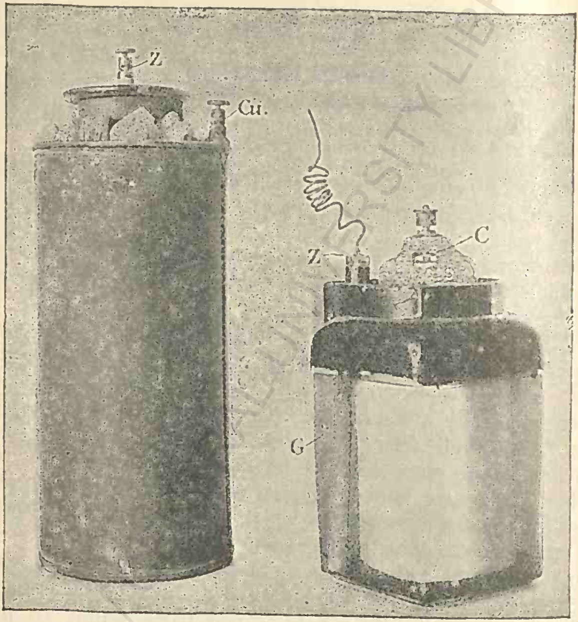


FIG. 157.—(i.) A Daniell cell, (ii.) a Leclanché cell.

consequently soon becomes polarised if used continuously; it soon becomes depolarised, however, if allowed to remain unused for a short time. A Leclanché cell has the advantage of requiring very little attention, and is for this reason very generally used in telegraphic work, in houses for working electric bells, and in any work where current is only occasionally required. The cell may not require renewing for months or years, and its failure to act is often due simply to evapora-

tion of the water from the solution of sal-ammoniac, which can be rectified by the addition of more water.

Both the bichromate and the Leclanché cells are sometimes termed **one-fluid cells**, in distinction to other types which are termed **two-fluid cells**, owing to the fact that the depolarising liquid is separated from the zinc and sulphuric acid by means of a porous partition.

The Daniell Cell.—In a Daniell cell copper and zinc are used as the metals, and sulphate of copper (*blue vitriol*) is used as a depolariser. The outer vessel (Fig. 157, i.) is of copper, and serves as the copper plate. The porous pot is surrounded by a strong solution of sulphate of copper, the strength of which is maintained by placing crystals of the sulphate on a perforated copper shelf near the top of the outer vessel. The zinc rod and dilute sulphuric acid are contained by the porous pot.

When the cell is in use the hydrogen generated by the action of the zinc on the sulphuric acid passes through the porous pot, and, instead of appearing on the surface of the copper, displaces copper from the copper sulphate. The result is, that pure copper, and not hydrogen, is deposited on the copper plate.

Hydrogen acts on **copper sulphate** and forms **sulphuric acid** and **copper**; or,

$$H_2 + CuSO_4 = H_2SO_4 + Cu.$$

If the cell is left standing for a long time, some of the copper sulphate will pass through the porous pot and will be decomposed by the zinc forming zinc sulphate and copper, the latter being deposited on the zinc rod. This effect will reduce the power of the cell, and it is consequently necessary to remove the liquids to separate bottles as soon as the experiments are completed.

The Grove Cell.—In this cell zinc and platinum are used as metals, and nitric acid (HNO_3) as a depolariser. In Fig. 158 a thin sheet of platinum **P** is surrounded by strong nitric acid contained in a flat porous pot **B**. The zinc plate **Z**, bent into the form of a letter **U** and embracing the porous pot on both sides, is immersed in dilute sulphuric acid (1 in 8) contained in the outer vessel **A**. The hydrogen, in passing

through the nitric acid in order to appear at the platinum plate, is oxidised by the nitric acid. The nitric acid itself is decomposed to brown fumes of nitric peroxide, which are very soluble in the acid and consequently do not produce polarisation. When the cell is in use the acid soon becomes saturated with the brown fumes, any further use results in the

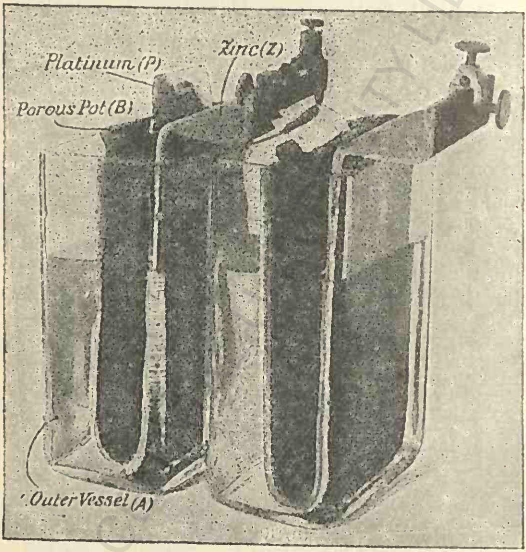


FIG. 158.—Two Grove cells.

fumes escaping into the room; it is therefore advisable to place the battery in a fume-cupboard, since nitric peroxide is injurious to health and also to any metal work.

The E.M.F. of a Grove cell is approximately twice as great as that of a simple cell, and it is therefore a useful source of current; but the battery should be taken apart after two or three hours' working, since the slow percolation of nitric acid through the porous pot will cause the zinc to be rapidly attacked. The metal plates and porous pot should be well

washed immediately after use, and the acids stored for future use in separate bottles.

The Bunsen Cell.—The chief consideration militating against the general use of the Grove cell is the original cost of the platinum plates. In the Bunsen cell plates of carbon are used instead of platinum, but in every other respect it resembles the Grove cell. The porous pot (Fig. 159), containing the carbon plate C, is cylindrical; the zinc plate is bent into the form of a cylinder so as to completely surround the porous pot.

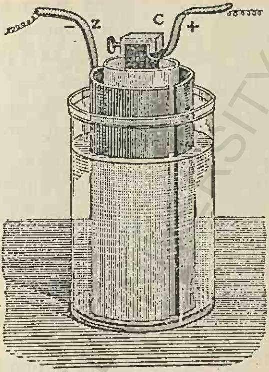


FIG. 159.—A Bunsen cell.

Cells in series and in parallel.—In many experiments it is necessary to use a stronger current than would be obtained from a single cell. Four Bunsen cells (quart size), or the same number of Grove cells, form a convenient source of current. The cells may be connected together **in series**, **in parallel**, or **in multiple-arc**. Fig. 160 (i.) represents four Bunsen cells connected together *in series*, the zinc plate of one cell being joined to the carbon plate of the next, and so on; a long thin line represents a carbon plate and a short thick line a zinc plate. The potential difference between the carbon plate C at one end of the battery and the zinc plate Z at the other end will be four times as great as that which would be obtained by using only one cell (see p. 236).

Fig. 160 (ii.) represents four cells joined together *in parallel.* All the zinc plates are connected together, and also all the carbons are connected together, thick copper wire being used for the purpose. The potential difference between the two terminals of the battery will be the same as if one cell only had been used; in fact, the arrangement is exactly the same as if one large cell, with plates four times the size of those in either of the constituent cells, had been used. The same potential difference would, indeed, be obtained if a minute cell, no larger than a sewing thimble, were used, but a larger cell has other advantages which will be explained in a subsequent chapter. The potential difference depends only upon what metals and acid are used in the construction of the cell, and is quite independent of the size of the cell.

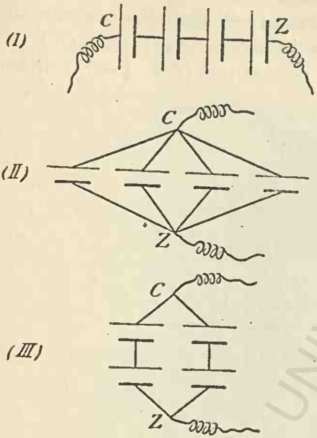


Fig. 160.

Fig. 160 (iii.) represents the four cells joined together *in multiple arc.* The potential difference between the terminals is equal to twice that obtained from a single cell—in other words, the potential difference is the same as that obtained by joining two cells in series. The advantage of using four cells in this manner, instead of two single cells, depends upon the fact that the arrangement is equivalent to two large cells, each twice the size of a single cell.

The Commutator, or Current Reverser.—It is advisable to have a simple appliance for reversing the direction of the current in a wire without interchanging the connections of the wire to the battery. Fig. 161 represents a simple form of commutator. It consists of a square block of wood, with a circular hole bored in each corner to serve as mercury cups. The cups are connected diagonally by thick copper wires.

Two thick copper wires dip into two of the cups on one side of the block and serve as terminals to which the ends of the wire are connected. The swinging arm consists of two pieces of bent copper wire which are insulated from each other by means of a short piece of glass tubing, which also serves as a handle. The arm carries two pieces of thick wire bent into an

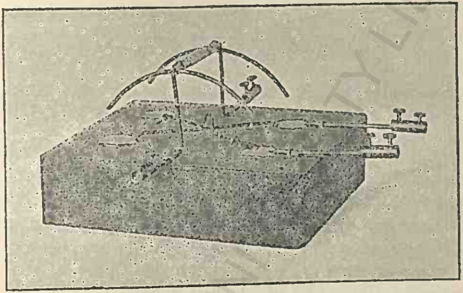


FIG. 161.—A simple form of commutator.

arc, which can be made to dip into either pair of mercury cups by swinging the arm over in the required direction. The poles of the battery are connected to the ends of the arm by means of binding-screws. The various parts can be fixed in position by means of wire staples. When the arm is in a vertical position the circuit is broken and no current flows along the wire. If the arm is swung to the left the current will traverse the wire in the reverse direction to that which is traversed when the arm is swung to the right.

CHIEF POINTS OF CHAPTER XVII

Voltaic Cells.—The various types of voltaic cells chiefly differ from one another in the method adopted for preventing polarisation, and the chief types are :—(i.) *The Bichromate* (depolariser, bichromate of potash); (ii.) *The Leclanché* (depolariser, manganese dioxide); (iii.) *The Grove* (depolariser, nitric acid); (iv.) *The Bunsen* (depolariser, nitric acid); and (v.) *The Daniell* (in which polarisation is prevented by a chemical reaction in which hydrogen displaces copper from copper sulphate).

Methods of connecting several cells together to form a battery.—Cells may be connected (i.) *in series*, by placing the cells symmetrically in a row and connecting together alternate + ve and − ve poles; (ii.) *in parallel*, by connecting all the + ve poles together, and all the − ve poles together; (iii.) *in multiple arc*, by connecting them partly in series and partly in parallel.

The Commutator is a device for changing the direction of flow of a current without making any disconnections.

Questions on Chapter XVII

1. When a galvanic cell, consisting of zinc and copper plates immersed in dilute sulphuric acid, has its terminals joined by a wire, the E.M.F. rapidly decreases. How do you account for this? Describe a cell designed to prevent this decrease in E.M.F., and explain how it acts. (Lond. Matric. 1896.)

2. A glass cell is divided into two compartments by a porous partition. One compartment contains a strong solution of copper sulphate, and the other dilute sulphuric acid. A copper plate and a zinc plate, which dip into these respectively, are joined to the terminals of a galvanometer, the needle of which is deflected. State and explain how the deflection will be altered if the copper sulphate is replaced by dilute sulphuric acid. (1898.)

3. What are the materials used in the construction of a Daniell cell? and what chemical changes occur in the cell when in action? (1888.)

4. Describe a simple piece of apparatus for reversing the direction of an electric current through any piece of apparatus such as a galvanometer, and show how it is to be connected up to the galvanometer and to the battery.

5. Two galvanic cells are made of exactly the same materials, but in one cell the plates are much larger than in the other. What would be the effect of introducing both into a circuit so that they tend to send currents in opposite directions? Give reasons for your answer. (1895.)

6. Explain the terms *in series* and *in parallel* as applied to the cells of a voltaic battery. Give diagrams.

7. Two galvanic cells are made by dipping (i.) plates of zinc and platinum into a beaker of dilute sulphuric acid, and (ii.) plates of zinc and copper into another beaker containing the same liquid. The plates can be connected by copper wires. Explain with diagram how the two cells may be connected in series so as to (i.) strengthen, (ii.) weaken, the current produced by one of them. (1898.)

CHAPTER XVIII

MAGNETIC EFFECTS OF AN ELECTRIC CURRENT

Apparatus required.—Battery. Commutator. Compass-needle. Copper wire. Thin and thick copper wire. Iron filings. Paraffined paper. Floating battery. Bar-magnet. Gutta-percha covered wire. Magnetised needle fixed to a cork. Spirals of wire (Fig. 170).

When two conductors at different potentials are connected by a wire, positive electricity flows from the conductor at higher potential to the conductor at lower potential. This is observed when the copper and zinc plates of a simple voltaic cell are connected together by means of a wire, and the effect which the wire then has on a neighbouring compass-needle has already been used (Expt. 138) as a means of detecting the phenomenon. This effect was first observed by Oersted of Copenhagen, in 1819.

Oersted's Experiment. Expt. 146.—(i.) Connect the poles of a Grove or Bunsen cell to a commutator, the other terminals of which (Fig. 161) are connected by means of a long thin wire. Stretch out a length of the wire so that it lies horizontally in the magnetic meridian. Place a compass-needle underneath the wire and *complete the circuit* by swinging over the arm of the commutator so as to allow the current to pass along the wire. Observe how the needle is deflected. *Break the circuit* by moving the commutator arm into the vertical position, and observe that the needle swings back into the meridian. Reverse the direction of the current by swinging the commutator arm over in the

opposite direction. Observe that the needle is again deflected, but in the opposite direction.

(ii.) While the current is still passing along the wire vary the distance of the wire above the compass-needle. Notice how the deflection decreases as the distance increases.

(iii.) Repeat the observation in Expt. i., using two cells connected together in series instead of one cell. If the distance between the wire and the compass-needle is the same in both cases, a greater deflection is observed than when only one cell is used.

Evidently the current traversing the wire creates a magnetic field in the space near to the wire, and the direction and strength of the magnetic forces depend upon the direction and strength of the current. The existence of this magnetic field may be verified by a further experiment.

Expt. 147.—Connect two fairly thick copper wires to the poles of a battery of three or four Grove or Bunsen cells in series, and join the free ends of these wires by a short length (about 10 cms. long) of thin copper (or platinum) wire. Dip the thin wire into iron filings, and notice how the filings cling to the wire. Break the circuit and observe that the filings at once fall off.

The magnetic forces near to the wire are evidently strong enough to overcome the weight of the filings. If there is a magnetic field *below* the wire we should expect a field to be present above, and on each side of, the wire—we should expect the field to be symmetrically distributed round the wire.

Expt. 148.—(i.) Lay a sheet of paraffined paper on a sheet of cardboard, and bore a *small* circular hole through the centre of both sheets. Clamp the cardboard and paper in a horizontal position, and thread a straight piece of thick copper wire (40 cms. long) vertically through the circular hole. Clamp the wire in this position, and sprinkle iron filings on the paper. Use a battery of four cells or, preferably, of six cells connected together in two rows of three cells each (p. 250). Complete the circuit, and tap the cardboard. Break the circuit, and notice how the filings have arranged themselves in circles concentric with the wire.

Fix the filings in position by warming the paper with a Bunsen flame (Fig. 162).

Which is the positive direction of these circular lines of force? In other words, would a single north-seeking pole appear, to an observer looking *down* on the experiment, to travel round the wire in the same direction as the hands of a clock or in the opposite direction?[1]

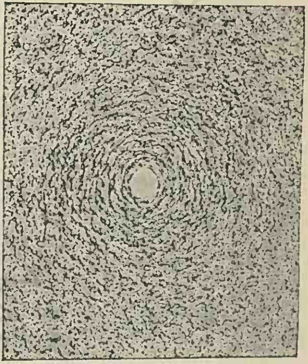


FIG. 162.—Map of the magnetic field perpendicular to a wire conveying a current.

(ii.) Place a compass-needle on the paraffined paper and near to the wire. Complete the circuit and observe the direction in which the needle points when placed to the north, south, east, and west of the wire. Reverse the direction of the current and notice that, in each position, the direction in which the needle points is reversed. Adjust the connections so that the current is passing *down* the wire, observe the direction of the needle, and verify the following rule:—

The positive direction of the lines of force appears to be clockwise to an observer looking along a wire which is conveying a current away from him.

Maxwell's Corkscrew Rule.—The same result is expressed in Maxwell's Corkscrew Rule, as follows:—**Imagine a corkscrew being screwed along the wire in the direction in which the current is passing. The direction in which the thumb rotates indicates the positive direction of the lines of force.**

The distribution of the lines of force round a wire conveying a current afford a clear explanation of Oersted's Experiment, and it also suggests that the deflection of a compass-

[1] These directions are termed *clockwise* and *anti-clockwise*.

needle placed *above* a wire conveying a current will be in the opposite direction to that observed when the needle is below the wire.

EXPT. 149.—Repeat Expt. 146. Also place the needle *above* the wire, and observe the direction of the deflection with the current direct and reversed. Verify the results tabulated below.

Current passing from	Needle above (or below) wire.	North-seeking pole deflected towards
South to North	below	West
,, ,,	above	East
North to South	below	East
,, ,,	above	West

Ampère's Rule.—The following rule was suggested by Ampère to include all these results :—**Suppose a man to be swimming in the wire in the same direction as the current, and with his face towards the needle; the north-seeking pole is deflected towards his left hand.**

It is important to notice in all these experiments that when the current ceases to pass along the wire the deflection of the needle simultaneously ceases. Hence the magnetic field is dependent for its maintenance upon the *flow of the electric current*, and it affords a distinct characteristic of the flow of electricity as compared with *electricity at rest*—for example, an insulated charged conductor has no effect on a neighbouring magnet.

Magnetic Field due to a Current in a circular Wire.—If a current is sent through a wire bent into the form of a circle it is clear (from Maxwell's Corkscrew Rule) that the space enclosed by the wire will be traversed by lines of force all travelling in the same direction. A horizontal cross-section through the centre of the circle would be similar to Fig. 163, which represents the current passing *down* through the paper at A, and returning *up* through the paper at B. The lines of force shown in the figure are those due to short

lengths of the wire near to A and B, and they are all in the direction from right to left. Outside the wire circle the direction of the lines will be from left to right. The lines of force due to all other portions of the wire will proceed in the same direction—in fact, Fig. 163 might just as readily be regarded as a vertical or inclined cross-section of the wire.

FIG. 163.

The magnetic field of the wire circle closely resembles that of a magnetised disc of steel, of which the thickness is equal to the diameter of the copper wire, the diameter equal to that of the wire circle, and magnetised so that the opposite faces of the disc have opposite polarity. Such a magnetised steel disc is usually termed *a magnetic shell*, and the magnetic shell which would possess a field of force identical with that due to the current in the wire circle is called *the equivalent magnetic shell of the circuit*. These remarks suggest that the wire circle with its current should resemble a magnet in other respects, *e.g.* that the right-hand face should have south-seeking polarity, and the left-hand face north-seeking polarity. This can be readily verified by means of De la Rive's Floating Battery.

De la Rive's Floating Battery. EXPT. 150.—(i.) Use the zinc and copper plates which were made for the simple voltaic cell. Pass the copper wires attached to these plates through holes in a flat cork, and protect the soldered joints with sealing-wax or varnish. Make a circular coil (about 5 cms. diameter, and of four or five turns) of thin cotton-covered copper wire, and bind the turns together with cotton. Fasten the free ends of the coil by means of binding-screws to the ends of the thick wires attached to the plates, and arrange the coil so that it is vertical when the cork is floating on dilute sulphuric acid contained in a large beaker or deep dish. Notice how the coil sets with its plane perpendicular to the magnetic meridian. Evidently the two faces of the coil exhibit magnetic polarity. Trace out the direction in which the current is passing, and verify the following rule:—

If the coil is held so that its face is perpendicular to the line of sight, and if the current appears to pass round the coil in a clockwise direction, then that face will have south-seeking polarity. If the direction is anti-clockwise, then the face will have north-seeking polarity (Fig. 164).

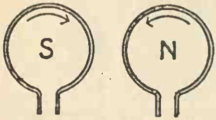


FIG. 164.

(ii.) Hold a pole of a bar-magnet near to the coil, and observe how the latter is either attracted or repelled, according to which face of the coil is directed towards the magnet. From the results obtained verify the clock-face rule stated above. Notice how the coil threads itself along the magnet if the latter

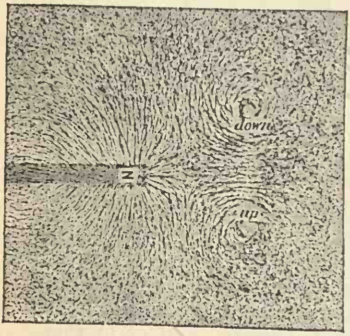


FIG. 165.

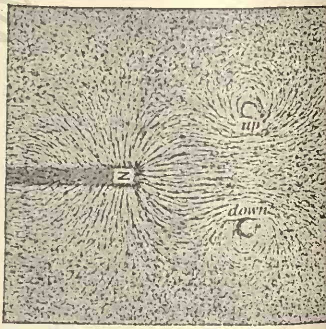


FIG. 166.

Combined magnetic fields due to a magnet and a circular wire conveying a current.

is held at a convenient height, and comes to rest opposite the centre of the magnet.

These results may be more readily understood by examining the distribution of the lines of force. *Repulsion* is shown in Fig. 165, and *attraction* in Fig. 166. In the latter case it is evident that the tension of the lines of force will tend to move the coil up to the centre of the magnet. An instructive

extension of this result may be shown by fixing the spiral and allowing the magnet freedom to move.

EXPT. 151.—Half immerse an open spiral of gutta-percha covered wire in a dish of water (Fig. 167). Float a small magnetised needle on a piece of cork, and pass a current through the spiral. Notice how the needle is not only attracted but also enters the coil and comes to rest opposite its centre.

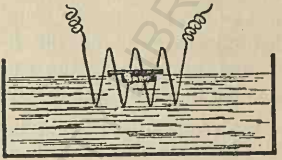


FIG. 167.—To illustrate Expt. 151.

Magnetic Field due to a Spiral of Wire conveying a Current.—If a single turn of wire conveying a current behaves like a magnetic shell, then several turns of wire placed face to face, and each turn conveying the same current in the same direction, would be expected to show magnetic properties similar to a row of magnetic shells placed with faces of opposite polarity in contact—in other words, a spiral of wire conveying a current should resemble an ordinary bar-magnet. The mutual actions of one spiral on another, both conveying a current, should also obey the ordinary laws of magnetic attraction and repulsion.

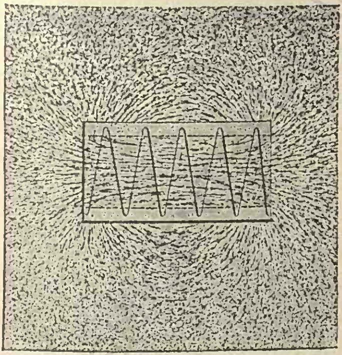


FIG. 168.—Magnetic field due to a spiral conveying a current.

EXPT. 152.—Wind a close spiral of cotton-covered copper wire on a cardboard tube (5 cms. diameter and 20 cms. long). Support a sheet of paraffined paper horizontally so that its plane coincides with the axis of the tube, having previously cut away portions of the paper so as to fit symmetrically round the tube. Sprinkle iron

filings over the paper, and obtain a map of the field due to a current passing through the spiral (Fig. 168).

Observe how closely this magnetic field resembles that of a bar-magnet. The hollow spiral enables us to obtain a map of the complete magnetic circuit, and the map indicates that the lines of force inside the spiral are parallel to the axis. (From theoretical reasoning the internal magnetic field of a bar-magnet would have the same form, but it is of course impossible to obtain a map experimentally.)

Fig. 169 explains how the internal field due to consecutive turns of the spiral will consist of lines of force parallel to the axis. The diagram represents a vertical cross-section through two turns of the spiral, and the current traversing the spiral is imagined to be passing down through the paper at W_1 and W_2, and to return upwards through the paper at W_3 and W_4. Consider only the forces due to short lengths of the spiral coinciding with the vertical plane of the diagram, and the action of such forces on a single north-seeking pole placed within the spiral. If the pole is placed at n_1 it will be acted upon by two forces—n_1r_1 due to the current at W_1, and n_1r_2 due to the current at W_2; the resultant force is n_1R_1 acting in a direction parallel to the axis. Similarly, if the pole is placed at n_2, the resultant force is n_2R_2 due to the current at W_3 and W_4.

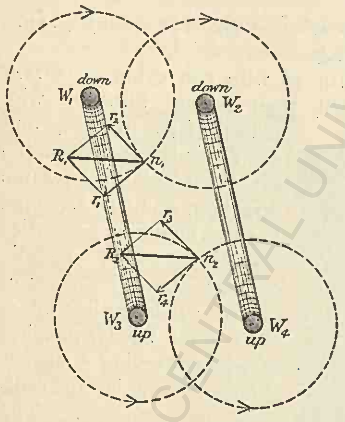


FIG. 169.—The magnetic forces, n_1R_1 and n_2R_2, inside a spiral are parallel to the axis of the spiral.

Electro-magnets.—The student has already learnt that a piece of soft iron becomes temporarily magnetised when placed in a magnetic field, and that the degree of magnetisation acquired is (within certain limits) proportional to the strength of the magnetic field. If a rod of soft iron is inserted inside a spiral of wire (see Fig. 9) conveying an electric current, the magnetic field within the spiral acts inductively upon the iron so that the magnetic polarity of the spiral itself

is augmented by the polarity acquired by the iron. As soon as the current ceases the polarity of both the spiral and the soft iron disappears. Such an arrangement is termed an **Electro-magnet.** By using a sufficiently strong current and soft iron it is possible to obtain electro-magnets of great strength.

EXPT. 153.—(i.) Select a cardboard or glass tube of sufficient diameter to allow a rod of soft iron to be inserted. Wind two or three layers of cotton-covered copper wire round the tube. Adjust the magnetometer as described in Expt. 63, and place the coil of copper wire on the scale about 20 cms. distant from the needle with its axis perpendicular to the meridian. Connect the ends of the coil to a single Bunsen cell. Note the deflection of the needle. Insert the soft iron core into the coil, and note the largely increased deflection. Break the circuit, and observe how the needle returns to zero.[1]

(ii.) Dip the electro-magnet used in Expt. (i.) into a heap of wire nails. Notice the great lifting-power which it has. Break the circuit, and notice how all the nails fall off. If the iron is not very soft it will retain a little permanent magnetism, and a few nails will remain attached to it.

If the iron bar and spiral are bent into the form of a horse-shoe we have a *horse-shoe electro-magnet* (see Fig. 11). If they are bent so that the two ends are brought completely together so as to form a solid ring, all the lines of force within the spiral become *closed magnetic chains*, and no external magnetic field can be detected; the iron core would then resemble the magnetised steel ring represented in Fig. 64.

Mutual Action of two Spirals.—Fig. 170 represents a simple form of apparatus for examining the mutual forces of two spirals through which a current of electricity is passing.

EXPT. 154.—Wind a spiral of fairly thick cotton-covered copper wire round a cardboard tube (5 cms. diameter and 20 cms. long). Fix each end of the spiral to the tube by tying the wire with thread which passes through small holes pierced in the cardboard. Bend the free

[1] The experiment may be made more instructive by substituting lengths of soft iron wire for the iron rod, and gradually increasing the number of wires in the coil.

ends of the wire along the outside of the tube and towards the centre, and again bend them at right angles so as to dip down into concentric mercury cups placed underneath. The mercury cups shown in the figure are made by gluing together two pill-boxes, of different diameter, one inside the other. Connect each mercury cup to an external binding-screw by means of copper

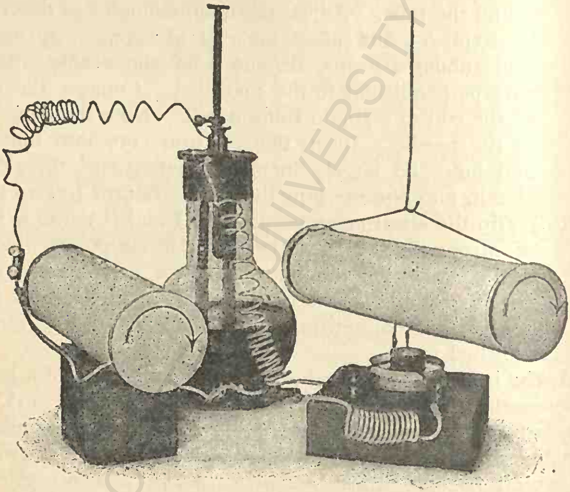


FIG. 170.—Apparatus to illustrate mutual action of two spirals.

wire. One of the ends of the spiral is bent so that it is in a vertical line with the suspension and dips into the inner mercury cup; the other end is bent so as to dip into the outer cup. The mode of suspending the spiral is clearly seen in the diagram (Fig. 170). Make a second spiral, which can be held in the hand in order to test its action on the suspended spiral when a current is traversing both spirals. Carefully note the direction of the current in both spirals, and verify the Primary Law of Magnetic Attraction and Repulsion.

Application of Oersted's Experiment to Telegraphy.—The instrument represented in Fig. 171 is frequently to be seen in provincial post-offices and in the telegraph offices attached to railway stations. In front of the disc of the instrument a vertical pointer is rapidly moving to and fro, and a tinkling noise is heard as long as the pointer continues to vibrate. This is the *single-needle telegraph instrument*,[1] and it is used for the purpose of transmitting messages between distant localities.

FIG. 171.—A single-needle telegraph instrument.

This instrument is similar in principle to the astatic galvanometer (p. 271), but the coil of wire and the magnetised needle are fixed vertically instead of horizontally. The coil and magnetised needle are fixed inside the instrument; the end of the axle on which the needle is mounted passes through the front of the instrument and carries the pointer.

One end of the coil is connected to a metal plate buried in the earth, and the other end is joined to a long insulated wire supported on telegraph poles leading to the distant post-office where there is a battery and a commutator. One terminal of the commutator is connected to the telegraph wire, and the other terminal is connected to a metal plate buried in the earth (Fig. 172). The two metal plates are always at the same potential (*zero*), and since the earth is a conductor it serves the same purpose as a very thick copper wire (shown by dotted line), the expense of which is thereby saved. By making use of the earth's conductivity in this manner only a

[1] First introduced by Cooke and Wheatstone in the year 1837.

single wire is needed in order to connect two offices together telegraphically.

A special form of commutator is used which consists of two strips of metal (L and R) which are capable of moving up and down like the notes of a piano.[1] In their upper position they are both in contact with a cross-piece of metal (A) connected to the – ve terminal of the battery. If L is pressed down its contact with A is broken and contact with B is made, thus connecting the – ve terminal of the battery to earth; B (and therefore L) will have + ve potential, and a current will flow along the telegraph wire towards the distant

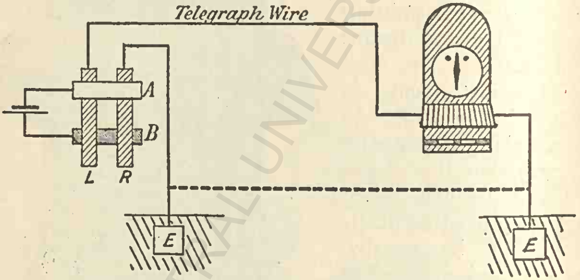


FIG. 172.—Diagram of a simple telegraphic system.

end causing the needle in the instrument to deflect in a certain direction. If L is released and R pressed down into contact with B a current in the reverse direction is obtained, and the needle will be deflected in the opposite direction. A recognised code of signals is adopted whereby the letters of the alphabet are represented by various combinations of left and right motions of the needle; thus a single swing to the left represents the letter *e*, a single swing to the right represents *t*, a swing to right followed by a swing to left

[1] A working model of this commutator may readily be made from four strips of sheet brass. The fixed ends of L and R are raised above the base-board by screwing them to a narrow strip of wood about 1.5 cm. high. The strip A is fixed at both ends to raised blocks of wood of such a height that both L and R touch its under surface when at rest. The strip B is fixed to the base-board. In order to facilitate making connections, binding-screws should be used instead of ordinary screws.

indicates *n*, a swing to left followed by one to the right represents *a*. All the other letters are formed of two, three, or four combinations.

In order that the telegraph operator may be able to interpret messages *by ear* as well as *by sight*, two small pieces of tinplate are fixed on either side of one end of the pointer, the movement of which will cause the familiar tinkling sound when the instrument is working. The pieces of metal are cut to slightly different sizes in order that the deflections in opposite directions may be readily distinguished by the sound emitted.

Chief Points of Chapter XVIII

Oersted's Experiment proves, by the action of a wire conveying a current on a neighbouring magnet, that the wire is surrounded by a magnetic field. A map of the field indicates that the magnetic lines of force are circular and concentric with the wire, and that a magnet will be influenced both above and below the wire. The *direction* of the lines of force may be remembered by means of "The Clock-face Rule" or by "Maxwell's Corkscrew Rule."

Ampère's Rule affords a simple method of remembering the relationship between the direction of the current and the observed deflection of a magnet according to the relative positions of the wire and magnet.

The Magnetic Field due to a current in a wire bent into the form of a circle.—Lines of force are threaded through the space enclosed by the wire, and the direction of the lines is reversed when the direction of the current is reversed. These lines give south-seeking polarity to the face by which they enter the circular space, and north-seeking polarity to the face from which they emerge; these magnetic properties make it equivalent to a *thin magnetic shell.* The relationship between the direction of the current and the polarity generated is expressed in the following rule:—*If the current appears to the observer to traverse the wire in a clock-wise direction, then that face has south-seeking polarity; if the direction is anti-clockwise, the polarity is north-seeking.*

The Magnetic Field due to a straight spiral of wire conveying a current is the resultant field of each turn of the spiral. A map of the field indicates that the distribution of the lines of force is similar to that of a bar-magnet. The lines of force inside the spiral are approximately parallel to the axis.

The mutual actions of two spirals conveying currents are similar to the mutual actions between two magnets.

Application of Oersted's Experiment to **Telegraphy**, in which the letters of the alphabet are interpreted by various combinations of left and right deflections of a magnetised needle. In practice, a special type of **commutator** is used.

Questions on Chapter XVIII

1. A long straight wire is stretched on a table in the direction of the magnetic meridian, and a dip circle, with its plane parallel to the magnetic meridian, is placed on the table near to the wire and on the west side of it. Will the dip of the needle be altered when an electric current is passed along the wire from south to north, and, if so, how? Give reasons. (1896.)

2. A straight horizontal wire is placed near and parallel to a compass-needle, and in the same horizontal plane with it. If a current is then passed through the wire, what effect is produced on the needle, and what occurs if the wire is (i.) slightly raised, (ii.) slightly lowered? (1898.)

3. A strong electric current flows through a copper wire which passes through the centre of an iron ring, and is at right angles to the plane of the ring. Describe the magnetic state of the ring. (1892.)

4. A current is flowing through a rigid copper rod. How would you place a small piece of iron wire with respect to it so that the iron may be magnetised in the direction of its length? Assuming the direction of the current, state which end of the iron will be a north pole.

5. Two compass-needles are arranged near each other so that both point along the same straight line. A wire connecting the platinum and zinc ends of the battery is stretched vertical half-way between the needles. How will the current in the wire affect the needles, and how will the result depend upon whether the platinum terminal is connected with the upper or lower end of the wire respectively? (1887.)

6. Two long wires are placed parallel to each other in the same horizontal plane and in the magnetic meridian. A magnetic needle capable of turning in any direction about its point of suspension is placed exactly half-way between them. How will it behave if the same electric current flows through the easterly wire from south to north, and through the westerly wire from north to south? (The action of the earth on the magnetic needle may be neglected.)

7. A wire lies east and west (magnetic) immediately over a compass-needle. How is the direction in which the needle points affected when a *strong* current flows through the wire (1) from west to east, (2) from east to west? (1889.)

CHAPTER XIX

GALVANOSCOPES AND GALVANOMETERS

Apparatus required.—Examples of the astatic, tangent, and mirror galvanometers. Round bottles of various sizes. Metre scale and square wooden blocks. Paper strips.

The action of the magnetic field, created by a current of electricity passing along a wire, on a neighbouring magnet may be used as a means of detecting currents of electricity. Moreover, since the strength of the field depends upon the strength of the current, it is also possible to apply the same principle to the comparison of the strengths of various currents. An instrument for *detecting* an electric current according to this principle is termed a **Galvanoscope**, and instruments for *measuring* the strength of a current are termed **Galvanometers.**

The Simple Galvanoscope.—The principle of the galvanoscope can be readily examined by experimenting with the magnetometer described on p. 54.

EXPT. 155.—Cover the magnet and scale of the magnetometer with a shallow ring of cardboard, over which is placed a sheet of glass (see Fig. 40). Place the magnetometer on a box, allowing the end on which the needle is supported to project beyond the side of the box, so that a wire can readily be wrapped round the instrument, and adjust its position so that its length is perpendicular to the meridian. Connect the poles of a voltaic cell by means of a long thin copper wire (cotton-covered). Hold a portion of the wire so that its length is in the meridian, and bring it just over the

needle and as near to it as possible. Observe the deflection.

Still keeping the portion of wire above the needle in position, wrap the wire round under the instrument, so that a portion of the wire is just *underneath* the needle. Observe that the deflection is now greater than before.

This result would be expected by applying Ampère's Rule, which shows that the current in the wire above and below the needle will both tend to deflect the needle in the same direction.

Wrap the wire once more round the needle, and observe the still greater deflection. Wrap several more turns round the needle, and note the deflection during the process.

The magnetic field which causes the deflection of the needle is the resultant field due to all the fields created by individual turns of the wire. In this manner the deflection caused by the current is multiplied, and, by increasing the number of turns sufficiently, it is possible by this means to detect an extremely weak current. This is the principle on which all galvanoscopes are constructed.

The amount of deflection obtained is determined by the relative strengths of the magnetic forces due to the current and to the earth's magnetic field. The former tends to pull the needle into a position at right angles to the meridian, while the latter tends to pull the needle back into the meridian.

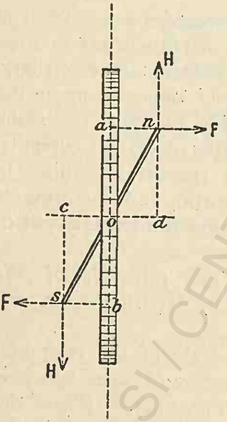


FIG. 173.—The principle of a galvanometer.

These opposing forces may be represented by Fig. 173, in which *ab* represents the coil of wire, and *ns* the magnetised needle. If H and F are the strengths of the magnetic fields due to the earth and to the current respectively, and if *m* is the magnetic pole strength of the needle, then the forces acting on both *n* and *s* will be $(m \times H)$ and $(m \times F)$. Each pair of forces acts on the needle like a mechanical couple. Each couple tends to rotate the needle in opposite directions,

and the needle finally comes to rest in such a position that the moments (p. 36) of these couples round the centre of the needle are equal and opposite.

$$\text{Moment of couple } m\text{H} = \text{moment of couple } m\text{F},$$
$$m\text{H} \times cd = m\text{F} \times ab,$$

or,
$$m\text{H} \times 2od = m\text{F} \times 2ao.$$

Hence $m\text{F} = m\text{H} \times \dfrac{od}{oa} = m\text{H} \times \dfrac{an}{oa} = m\text{H} \times \text{tangent of angle } aon;$

or, the tangent of the angle of deflection $= \dfrac{m\text{F}}{m\text{H}} = \dfrac{\text{F}}{\text{H}}$.[1]

This formula assumes that the magnetic field due to the coil is uniform, but in reality it is only uniform in a very small region round the centre of the coil, and the formula would therefore only hold good if the magnet were very short.

The Sensibility of a Galvanoscope or Galvanometer.—The sensibility of such instruments may be defined as the amount of deflection obtained with a given current of electricity. The sensibility is great if a considerable deflection is obtained with an extremely weak current.

How to increase the Sensibility.—From the result obtained in the previous section it is evident that the deflection obtained may be increased by constructing the instrument so as either to increase the force F or to diminish the force H.

(*a*) *By increasing* F.—The deflecting force F may be largely increased by making a coil with as many turns of wire as possible. Within certain limits the force F increases with the number of turns of wire. This method is adopted in the construction of simple forms of galvanoscopes.

(*b*) *By diminishing* H.—The controlling force H may be diminished by two methods :—

(i.) **Nobili's Method.**—By using an astatic pair of magnetised needles (Fig. 90). If the two magnets are of exactly equal strength and size, the force tending to make the one magnet set in the magnetic meridian is exactly neutralised by the force acting on the other magnet, and the astatic pair

[1] It will be observed that the deflection is independent of the magnetic strength of the needle.

comes to rest in any position. In practice it is impossible to obtain two magnets so identically alike, and the pair comes to rest in the meridian in obedience to the force due to the stronger magnet. If m and m' are the magnetic strengths of the poles of the magnets, the forces due to the earth's field acting on the magnets will be mH and m'H, and the resultant force acting on the astatic pair will be $m\text{H} - m'\text{H}$, or $(m - m')\text{H}$. In an astatic pair $m - m'$ is a very small quantity, so that the controlling force due to the earth is very small. Moreover, by placing the coil so that its upper layer lies between the needles (Fig. 174), the presence of the upper needle tends to increase the deflection of the lower needle, since, by Ampère's Rule, the deflection of the upper needle due to a current in the upper layer of the coil will be in the same direction as that of a reversed needle placed below the upper layer of the coil.

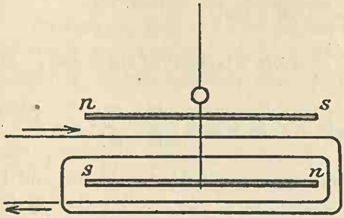


FIG. 174.—Principle of an astatic galvanometer.

(ii.) **Haüy's Method.**—By weakening the earth's field by placing a bar-magnet in a suitable position near to the instrument. By referring to Figs. 47 and 48 it will be clear that if the needle of the instrument occupies the position of one of the neutral points in the resultant field due to the earth and the magnet, it will come to rest in any direction. If the magnet is moved a little farther away from the instrument it will obey the forces due to the earth, but these will be much weaker than if the magnet were withdrawn. Fig. 48 explains how this result may be obtained by placing the magnet vertically over or under the instrument. Fig. 47 explains how the magnet may be placed with its axis in line with the needle's axis, and with its south-seeking pole directed towards the north.

The Astatic Galvanometer.—This instrument derives its name from the fact that an astatic pair is used as its magnetised needle. The pair is hung by a single silk thread,

so that the lower needle moves freely inside a coil of wire wound on a wooden frame (Fig. 175). The torsion[1] of the fibre is sufficient to mask the controlling effect of the earth's field, and, in fact, it forms the controlling force in the instrument. The instrument is adjusted for use by levelling the

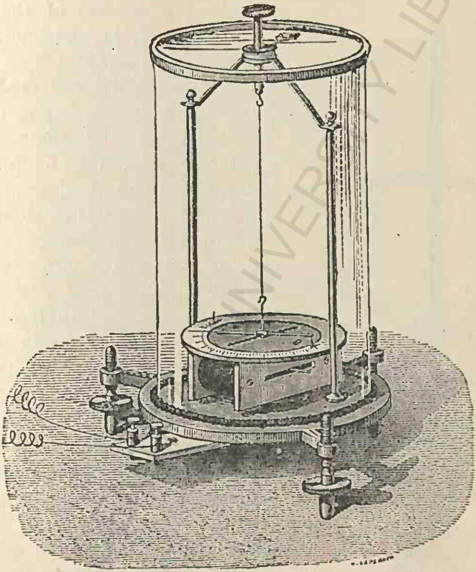


FIG. 175.—An astatic galvanometer.

base, and by turning the coil so that its length is parallel to the needles. The ends of the coil are attached to two binding-screws on the exterior of the instrument. The deflections are read off on a circular scale fixed to the top of the coil, and

[1] If the upper end of a fibre is fixed and the lower end is twisted through a certain angle, the fibre will tend to return to its original state, and the force with which it tends to do so is called the *Torsion*. Within limits, the magnitude of the force is proportional to the angle through which the lower end is twisted.

the upper needle serves as a pointer (or a long pointer is specially attached to the astatic pair). Since the deflecting force F is only uniform in a small region restricted to the centre of the coil, the deflection will only be proportional to the current when the deflections are small. It must also be remembered that the tangent law is not strictly applicable, since the torsion of the fibre, and not H, is the controlling force.

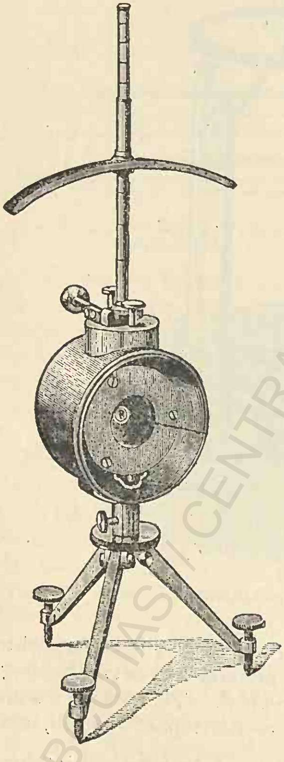


FIG. 176.—A mirror galvanometer.

The Mirror Galvanometer. — In principle this instrument is the same as the galvanoscope, but a far more accurate method of reading deflections is used than that afforded by the pointer and circular scale of the latter type. A small circular mirror of silvered glass is attached to the needle, and a beam of light is directed on to the mirror and reflected back to a horizontal paper scale placed at some distance from the instrument. A scarcely perceptible deflection of the needle will cause a considerable movement of the reflected beam of light on the scale. This type of instrument (Fig. 176) consists of a circular coil of many turns of thin silk-covered copper wire, in the centre of which a circular mirror is supported by means of a silk fibre. To the back of the mirror are attached three or four short lengths of magnetised watch-spring. A controlling magnet is supported above the instrument by a vertical upright, on which the distance of the magnet can be adjusted as required.

The Tangent Galvanometer.—In order that a galvanometer may obey the tangent law, it is necessary that the controlling force should be due to a uniform magnetic field (such as that of the earth), and that the field created by the current in the coil should be uniform within the region in which the needle is capable of moving. If the coil is circular and of

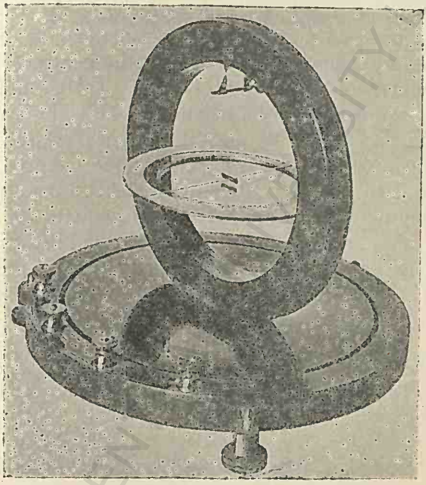


FIG. 177.—A tangent galvanometer.

considerable diameter, the field at its centre due to a current passing round it will be fairly uniform. Hence if a very short magnetised needle is suspended at the centre of a circular coil, which is placed with its plane in the magnetic meridian, then all the conditions for obeying the tangent law will be fulfilled. Such an instrument is called a **Tangent Galvanometer.**

Fig. 177 represents a suitable form of tangent galvanometer for simple experiments.[1] Three separate coils may

[1] The illustration represents the type of instrument used in the Birmingham Municipal Technical School.

advantageously be wound on the circular wooden frame (about 20 cms. diameter), and connected to separate binding-screws fixed to the base-board of the instrument. One coil may conveniently consist of three or four turns of thick copper wire, for use with fairly strong currents; the other coils may consist of fifty and one hundred turns (respectively) of thin copper wire, for use with weaker currents. A horizontal circular scale is fixed at the centre of the coil, and a magnetised needle (2 cms. long) is suspended by means of a single fibre of unspun silk just above the centre of the scale. A long pointer of drawn-out glass or of aluminium wire is attached to the centre of the needle and at right angles to its axis. The use of a silk fibre introduces torsion when the needle is deflected, but its controlling force is small compared with that due to the earth's magnetic field (unless the magnet is but feebly magnetised); this error, to which the instrument is liable, may be more completely avoided by pivoting the needle on a vertical metal point fixed through the centre of the scale. The needle is protected from air currents by placing a glass shade over the instrument.

The deflecting force F varies directly as the strength C of the current, the length l of the wire, and the strength m of the magnet's pole, and inversely as the square of the distance r between the wire and the pole. If the radius of the coil is r, and consists only of one turn, then the length of wire in the coil $= 2r \times \pi$.*

Hence $$F = \frac{C \times 2\pi r \times m}{r^2} = \frac{C \times 2\pi \times m}{r}.$$

The Electro-magnetic (or Absolute) Unit of Current.—So far the strength of a current has only been indicated by the symbol C, to which a numerical value cannot be given until a *unit* of current strength has been decided upon. The formula obtained in the previous section enables us to define a unit based upon the units of length, force, and magnet-pole strength (all of which have been previously defined). Thus, if $r = 1$ cm., and if the magnet-pole is of unit strength (*i.e.* if $m = 1$), then

$$F = 2\pi C \text{ dynes.}$$

The force will be equal to C dynes if we imagine that the current

* The symbol π is fully explained on p. 275.

only traverses $\frac{1}{2\pi}$ part of the wire circle (*i.e.* a length $=\frac{2\pi r}{2\pi}=r$), or round a part of the circle equal in length to the radius. If the force exerted by this portion of the circle is equal to one dyne, then the current strength will be equal to unity. Unit current strength may therefore be defined thus :—**A current has unit strength when 1 cm. length of its circuit, bent into the form of an arc of 1 cm. radius, exerts a force of one dyne on a unit magnet-pole placed at the centre of the arc.** This is known as the "absolute" electro-magnetic unit of current strength.

The Electro-magnetic Unit of Quantity.—The quantity of electricity conveyed by a current is proportional to the strength of the current and to the time during which it continues to flow. *Unit Quantity is that which is conveyed by unit current in unit time.*

Meaning of π.—The Greek symbol π is universally used in order to represent the numerical ratio between the circumference of a circle and its diameter, or

$$\pi=\frac{\text{circumference}}{\text{diameter}}.$$

This ratio is absolutely constant, whatever the size of the circle may be, and its numerical value is approximately $\frac{22}{7}$ (or, more accurately, 3.14159). The student may verify the constancy of this ratio by the following simple experiment :—

EXPT. 156.—Place a square block of wood on a metre scale lying on the table, and note the scale reading of an edge of the block. Place a Winchester quart bottle on the scale with its side touching the block of wood, and adjust the bottle so that its diameter coincides with the marked edge of the scale. Slide a second block of wood along the scale until its edge touches the opposite side of the bottle. Hold the block in position, remove the bottle, and note the scale reading of the edge of the second block. Subtract from this reading the scale reading of the first block. This gives the diameter of the bottle.

Cut a long narrow strip of paper, carefully wrap it round the lower part of the bottle, and see that it is at the same height from the table all round the bottle. Make a pencil mark on the overlapping ends of the paper. Remove the strip and measure the distance between the pencil marks. This gives the length of the circumference of the bottle.

Calculate the value of $\frac{\text{circumference}}{\text{diameter}}$.

Repeat this experiment with several round bottles of different

diameter, and note in each case how closely the ratio approximates to $\frac{22}{7}$.

Chief Points of Chapter XIX

A Galvanoscope is an instrument for *detecting* an electric current.

A Galvanometer is an instrument for *measuring* an electric current. If the magnetic field, due to the current, in which the magnetised needle is suspended is uniform, the tangent of the angle of deflection $= \frac{\text{deflecting force due to current}}{\text{controlling force due to earth}}$.

The Sensibility of a Galvanometer is the amount of deflection obtained with a given current.

Methods of increasing the Sensibility.—(i.) By increasing the number of turns of wire in the galvanometer, and so increasing the deflecting force. (ii.) By diminishing the strength of the earth's field by means of an auxiliary magnet. (iii.) By using a Nobili's astatic pair.

The Astatic Galvanometer, so named since an astatic pair is used as the magnetised needle of the instrument. The torsion of the fibre has far more controlling effect than the earth's field; hence the instrument does not obey the tangent law.

The Mirror Galvanometer is a form of galvanoscope in which the deflections are observed by means of a beam of light reflected from a small mirror attached to the needle.

The Tangent Galvanometer consists of a circular circuit of one or more turns at the centre of which a small magnetised needle is suspended. If the instrument has one turn the deflecting force $F = \frac{C \times 2\pi \times m}{r}$.

The Electro-magnetic Unit of Current is that which, when 1 cm. length of its circuit is bent into an arc of 1 cm. radius, will act upon a unit magnet-pole at the centre with unit force.

The Electro-magnetic Unit of Quantity is that which is conveyed by unit current in unit time.

The Symbol π is used in order to represent the ratio $\frac{\text{circumference}}{\text{diameter}}$ with respect to any given circle.

Questions on Chapter XIX

1. Describe and explain the construction of an astatic galvanometer and the cause of its sensitiveness. (1897.)

2. Describe the construction and use of a tangent galvanometer. (C. U. S. 1898.)

3. Describe the construction and method of use of some simple form of galvanometer. (Lond. Matric. 1897.)

4. Explain fully why the deflection of the needle of a tangent galvanometer is independent of the pole strength of the needle.

5. What is meant by the *sensibility* of a galvanometer? Describe some simple method of increasing the sensibility of (i.) an astatic galvanometer, (ii.) a mirror galvanometer.

6. How does the *controlling force* in an astatic galvanometer differ from that in a tangent galvanometer? And explain why the former instrument does not obey the tangent law.

7. Define the electro-magnetic unit of current, and explain how the definition is derived from the fundamental principle of the tangent galvanometer.

8. If an auxiliary magnet is to be used in order to increase the sensibility of a mirror galvanometer, state how you would place it relatively to the galvanometer and your reasons for doing so.

CHAPTER XX

ELECTRICAL RESISTANCE—OHM'S LAW

Apparatus required.—Bunsen cells. Tangent and Mirror galvanometers. No. 22 S.W.G. German silver, copper, and iron wire. No. 26 S.W.G. copper wire. Simple voltaic cell. Resistances. Three standard cells (preferably of Clark or Calomel type). A length of No. 32 German silver wire (2 metres long) stretched between terminals fixed to a board.

Resistance.—Electrostatical experiments (p. 133) have shown that substances may be classified as *conductors* and *non-conductors*. This property may be termed *conductivity*, or the same idea may be expressed in the opposite sense by the terms *resistivity* or *resistance* (*e.g.* we say that silk has *low conductivity* or *high resistance*).

Resistance may be defined as **the property which a body possesses of impeding the discharge of electricity through its substance.**

In electrostatical experiments all metals, the body, wood, and water, appear to be equally good conductors—yet the student may have noticed that in voltaic experiments no special precautions have been adopted in thoroughly insulating the apparatus. This apparent difference in experimental treatment is due to the fact that the potential differences generated by electrostatical methods are vastly greater than those obtained by voltaic methods—a contrast which is very evident in the experiments on Contact Electricity—and the rate of discharge through any substance depends directly upon the potential differences. For this reason a substance which

appears to discharge readily in electrostatical experiments need not necessarily do so in voltaic experiments. For the small potential differences obtained in simple voltaic experiments, the body, the table, etc., may be regarded as insulators.

By carrying out experiments with small potential differences (such as that from a few voltaic cells) we are able to prove that metals not only have the least resistance, but that different metals have not all the same degree of resistance. We can obtain information on Resistance by bearing in mind that if a constant potential difference is maintained between two points in a conductor, an electric current will pass between the two points, and the magnitude of the current will depend upon the resistance of the conductor; the current may be determined by allowing it to pass through some simple form of current-measurer (such as a tangent galvanometer).

The Resistance of a Wire depends upon the Metal, its length, and its cross-section.[1] EXPT. 157.—

(i.) Connect one end of a piece of German-silver[2] wire (No. 22,[3] 2 metres long) to one pole of a large Bunsen cell (or an accumulator), and connect the other end to a terminal of the short thick coil of a tangent galvanometer. Connect the other terminals of the cell and the galvanometer together by means of a short copper wire. The current traversing the German-silver wire also traverses the galvanometer, and the tangent of the angle of deflection is a measure of the magnitude of the current. Note the deflection.

(ii.) Break the circuit between the cell and the German-silver wire and insert into the circuit another piece of the same wire (1 metre long). The current is now opposed by the resistance of a total length of 3 metres of German-silver wire, and the current is *less* than before. Evidently the resistance of a wire depends upon its length.

[1] The experiments described in this section are simply qualitative, and the student is referred for fuller information to the experiments with Wheatstone's Bridge in Chapter XXI.

[2] German silver is an alloy of the following metals :—copper 60 parts, zinc 26 parts, and nickel 14 parts.

[3] These numbers refer to the *Standard Wire Gauge* (S.W.G.).

(iii.) Remove the metre length of German-silver wire, and substitute for it a metre length of copper wire (No. 22, S.W.G.). Note the deflection. The current is greater than in (ii.), but less than in (i.), showing that the resistance of copper is less than that of German silver.

(iv.) Remove the copper wire, and substitute for it a metre length of iron wire (No. 22, S.W.G.). The deflection observed indicates that iron is a better conductor than German silver, but not so good as copper.

(v.) Remove the iron wire, and substitute for it a metre length of No. 26 copper wire. The deflection indicates that a thin copper wire offers more resistance than a thick one.

Liquid Conductors, and therefore Voltaic Cells, have Resistance.—This fact was anticipated in the previous section by recommending the use of a *large* Bunsen cell or an accumulator; the cell itself has resistance, and therefore the *total* resistance in the circuit is only partly due to the connecting wires.

Just as the resistance of a wire depends upon the metal, its length, and its cross-section, so also does the resistance of a voltaic cell depend upon the materials of which it is made, and upon the length and cross-section of the liquid which the current has to traverse between the two poles of the cell. This can be readily shown by means of a modified form of the simple voltaic cell.

EXPT. 158.—Pierce the axis of an ordinary cork with the supporting wire of the copper plate of a simple voltaic cell, and mount the zinc plate on a cork in a similar manner. Bore two transverse holes through both corks on opposite sides of the axis, and of sufficient size to admit lengths of glass rod. Support the two corks on two parallel pieces of glass rod resting across the top of a large beaker in such a manner that the distance apart of the plates can be readily varied. Fill the beaker with very dilute sulphuric acid, and connect the plates to the thick coil of a tangent galvanometer by means of copper wires. Place the plates close together and observe the deflection. Separate them gradually and observe how the deflection diminishes, showing that the

resistance of the cell is increased when the length of the liquid column between the two plates is increased.

Now remove some of the acid by means of a pipette so as to reduce the cross-section of the liquid column. Notice how the deflection diminishes as the liquid gets lower and lower.

This explains the advantage of using a large cell instead of a small one. The E.M.F. of the cell simply depends upon the materials used and is quite independent of the *size;* but the resistance depends very largely upon the size, and only becomes negligible when a cell with large plates close together (such as an accumulator) is used.

Current depends upon Resistance.—That the strength of the current depends upon the resistance in the circuit is an obvious conclusion from the experiments in the preceding section.

Current depends upon E.M.F.—We should anticipate that the strength of the current flowing along a wire would depend upon the difference of potential between the two ends (or, in other words, upon the E.M.F. of the voltaic cell or battery).

EXPT. 159.—Connect up a large Bunsen cell, a 4-metre length of No. 22 German-silver wire, and the low resistance coil of a tangent galvanometer (as in Expt. 157). Note the angle of deflection. Substitute two large Bunsen cells connected together in series instead of the single cell, and note the angle of deflection. Obtain the numerical values of the tangents of these angles from a table of tangent values, and observe that the value is nearly twice as great in the second case. By using two cells instead of one cell we have doubled the E.M.F. in the circuit, but the resistance has also been slightly increased since the additional cell has resistance, hence the current is not quite twice as great. If we used cells which had no resistance the current passing through the wire would be exactly twice as great. We may say that *the current in a wire is directly proportional to the potential difference between its two ends.*

This is known as *Ohm's Law*, which can be more rigorously proved by the method described in the following section.

Ohm's Law.—G. S. Ohm,[1] in 1826, conducted original experiments which resulted in the statement of the following simple relationship: **In any wire at uniform temperature, the current is directly proportional to the potential difference between its ends**; or, **E/C** is a constant ratio (where **E** and **C** represent the potential difference and the current respectively).

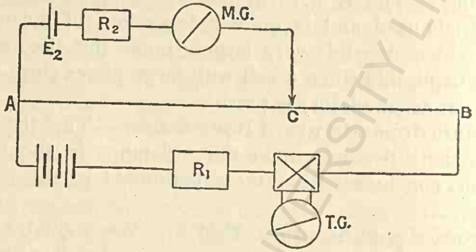


FIG. 178.—Proof of Ohm's law.

The numerical magnitude of the ratio **E/C** is a measure of the *Resistance* of the conductor. The constancy of the ratio **E/C** may be proved by applying the following principle: If any two points (A and C, Fig. 178) on a long thin wire AB, conveying a current, are touched by the ends of a thin wire AR_2C, a weak current will be generated and will traverse the thin wire from A to C (R_2 is a *high* resistance, *e.g.* a pencil line drawn on matt-glass). This weak current may be detected by including in its path a delicate galvanometer (MG). We can also include in the same circuit another source of electromotive force E_2 (say, a standard cell), placed so as to tend to send a current in the opposite direction. If this *opposing* electromotive force is equal to that due to the potential difference between A and C, then no current will traverse the wire, and no deflection will be produced in MG. The point C may be determined by trial, and the strength of the current between A and C may be observed by inserting a tangent galvanometer (TG) in the circuit. If *two* standard cells are used instead of E_2, and if C remains fixed, it will be found necessary to *double*

[1] G. S. Ohm (1789-1854) was the son of a German locksmith, and was appointed professor of physics in Munich in 1849.

the current strength between A and C in order to obtain no deflection in MG. If *three* standard cells are used, the current in AB must be made *three* times as great.

EXPT. 160.—Connect up the apparatus as shown in Fig. 178, and adjust R_1 so that a deflection of about 15° is obtained in TG. Find a point C such that no current traverses MG when one standard cell is used. Read the deflection in TG. Insert *two* standard cells in place of E_2. Make contact at C, reduce R_1 until there is no deflection in TG, and read the deflection. Repeat with three standard cells. Enter the observations thus:—

Standard Cells (n).	Deflections in TG. East End.	Deflections in TG. West End.	Mean Deflection.	tan α.	$\frac{n}{\tan \alpha}$.
1.	10°, 12°.1 } 11°.05	12°.4, 10° } 11°.2	11°.1	0.196	5.102
2.	20°.5, 22°.2 } 21°.3	22°.8, 20° } 21°.4	21°.35	0.391	5.115

Diagrammatic Representation of Resistance, E.M.F., and Current.—In Fig. 179 let AB represent a copper wire along which a current is flowing from A to B. If the wire is of uniform material and cross-section, the resistance of each cm. length of the wire will be the same; hence two cms. length would have twice the resistance of one cm. length. In other words, the resistance will be proportional to the length, and if AB represents the length of the wire it may also be regarded as a diagrammatic representation of its resistance.

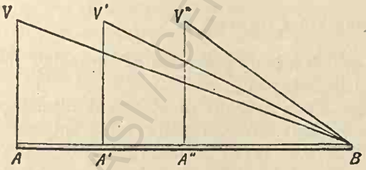


FIG. 179.

Let the potential at A be represented by AV, and that at B zero. The fall of potential along the wire will be uniform and represented by the line VB.

When the wire is shortened to A′B its resistance will be less than before, and V′B will represent the fall of potential. If the wire is still further shortened to A″B, then V″B will represent the fall of potential.

In our preliminary experiments we have observed that when the wire is shortened the current traversing the wire is increased: can this increase be suggested in the diagram? An increased current in our experiments is accompanied by an increase in the angle VBA in the diagram: can we regard the latter as a representation of the current?

This is evidently possible if we consider not the angle itself but rather the *tangent* of the angle, for then the tangent of $\text{VBA} = \frac{\text{VA}}{\text{AB}}$, or expressed in words—

$$\text{The strength of the current} = \frac{\text{difference of potential}}{\text{resistance}}.$$

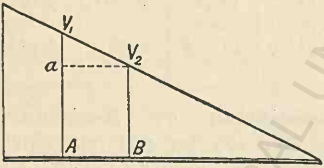


FIG. 180.

Fig. 180 is a similar diagram, which shows how the potential difference between *any* two points of a uniform wire may be indicated. The potentials at A and B are AV_1 and AV_2, and the potential difference is represented by the length V_1a.

CHIEF POINTS OF CHAPTER XX

Resistance is the property which a body possesses of impeding the discharge of electricity through its substance.

Comparison of Resistances.—The amount of electrical discharge in a given time (or, the current) between two points of a substance depends upon the potential difference (P.D.) between the two points; hence the relative resistances offered by different substances may be compared by comparing the currents which will traverse them when the same P.D. is used in each case.

The Resistance of a wire depends upon (i.) the metal, (ii.) its length, (iii.) its cross-section.

Liquid Conductors (and therefore Voltaic Cells) offer resistance to the passage of a current.

The Current traversing a wire depends upon (i.) the P.D. between its ends, (ii.) the resistance of the wire.

Ohm's Law.—*The current flowing through a circuit is directly proportional to the potential difference between its ends.*

Questions on Chapter XX

1. Define the term *Resistance*, and explain its relationship to the term *Conductivity*.

2. Describe a simple experiment by which it may be proved that a long wire has electrical resistance.

3. How would you prove experimentally that the resistance of a wire depends upon (i.) the metal, (ii.) its length, and (iii.) its cross-section?

4. A current is sent through a simple circuit by means of a single voltaic cell. Would more current be obtained from a cell with large plates than from a cell with small plates? If so, why? Would the distance between the plates influence the strength of the current?

5. The +ve poles of two Daniell's cells, one of them twice as large as the other, are connected together by a short wire, and the circuit is completed by connecting the −ve poles together by means of a long thin wire. Will any current traverse the circuit? Give reason for your answer.

6. The current strength depends upon the E.M.F. and the resistance. How can this be represented in a diagram?

7. State Ohm's Law, and describe an experiment by which the law may be verified.

8. You are given two voltaic cells which are identically alike. The current traversing a simple circuit, including the two cells in series, is not quite twice as great as that obtained when only one of the cells is used (the circuit being otherwise the same). Why is this?

9. A circuit includes an insulated battery and a galvanometer. Will the indication of the galvanometer be affected if a point in the circuit (*e.g.* the negative pole of the battery) is directly connected with the earth? Give reasons for your answer. (1891.)

10. How is polarisation prevented in the Daniell cell? How does a large Daniell cell differ from a small one in respect of (1) electromotive force, (2) resistance? (1903.)

CHAPTER XXI

UNITS OF E.M.F. AND RESISTANCE — PRACTICAL UNITS—OHM'S LAW APPLIED TO SIMPLE AND DIVIDED CIRCUITS—WHEATSTONE'S BRIDGE—GROUPING OF CELLS

Apparatus required. — Wheatstone Bridge. Two Daniell's cells. Astatic and tangent galvanometers. German-silver wire (Nos. 22 and 28 S.W.G.). Micrometer screw. Metre scale.

Electro-magnetic Unit of E.M.F. — The potential difference between two points has already been defined (p. 187) as equal to unity when unit work has to be done in conveying unit quantity of electricity from the point of lower potential to that at higher potential. The same definition may be applied to the electro-magnetic unit of potential difference, but the student must carefully note that the unit of quantity is not the same in electro-magnetic measure as in electrostatic measure—the former is based upon the magnetic action of a current traversing a wire, while the latter is based upon the mutual repulsion of two insulated charged spheres. **Unit difference of potential** (electro-magnetic) **exists between two points when unit work** (1 erg) **has to be done in order to convey an electro-magnetic unit of quantity between the two points.**

Electro-magnetic Unit of Resistance. — The close relationship between Current, E.M.F., and Resistance as expressed in Ohm's Law enables us to define the unit of resistance in terms of the other units. The electro-magnetic unit

of resistance is defined as follows:—**A conductor has unit resistance when unit potential difference between its ends causes a current of unit strength to flow through it.**

PRACTICAL UNITS OF CURRENT, QUANTITY, E.M.F., AND RESISTANCE

The Practical Unit of Current.—The electro-magnetic unit of current defined on p. 274 is found to be too large for practical purposes, and another unit is universally adopted which is equal to $\frac{1}{10}$ part of the electro-magnetic unit. This practical unit is called the **Ampère.**[1]

The Practical Unit of Quantity.—The *electro-magnetic* unit of quantity has been defined as the quantity conveyed by unit current in one second. The *practical* unit of quantity is that which will be conveyed by 1 ampère in 1 second, and is therefore equal to $\frac{1}{10}$ part of the electro-magnetic unit of quantity. This unit is called the **Coulomb.**[2]

The Practical Unit of E.M.F. (or Potential Difference).—The electro-magnetic unit (p. 286) is far too small for practical purposes, and a much larger unit is adopted which is equal to 10^8 electro-magnetic units. This larger unit is called the **Volt.**[3] (In order to express very large numbers it is convenient to use the index system of notation—thus 10^8 is the index notation representing 10 multiplied by itself 8 times, *i.e.* 100,000,000. The volt is therefore equal to one hundred million electro-magnetic units.)

The student may form a mental conception of the magnitude of the volt by the fact that the E.M.F. of the Daniell cell is 1.07 volts, the Grove cell 1.95 volts, the Bunsen cell 1.94 volts, and the Leclanché 1.46 volts.

The Practical Unit of Resistance.—A conductor is said to possess the practical unit of resistance when a potential

[1] André Marie Ampère (1775-1836), born at Lyons, a mathematician and physicist.

[2] Charles Augustin Coulomb (1736-1806), born at Angoulême.

[3] Alessandro Volta (1745-1827), professor of physics in Pavia University.

difference of 1 volt between its ends will cause a current of 1 ampère to flow through it. This unit is called the **Ohm.**

The following reasoning will enable its magnitude to be compared with that of the electro-magnetic unit of resistance:—$C=\frac{E}{R}$ is the general expression for Ohm's Law, but it may also be written $R=\frac{E}{C}$.

If $E=1$ volt, and $C=1$ ampère, then $R=1$ ohm.

But if we give to E and C their equivalent numerical values in electro-magnetic units, then R will also be expressed in the same units, or

$$1 \text{ ohm} = \frac{1 \text{ volt}}{1 \text{ ampère}} = \frac{10^8 \text{ electro-magnetic units}}{0.1 \quad \text{,,} \qquad \text{,,}}$$
$$= 10^9 \text{ electro-magnetic units.}$$

Practical Application of Ohm's Law.—By giving to the symbols C, E, and R their numerical values in practical units, we are able to regard the expression $C=\frac{E}{R}$ as a correct mathematical equation, and to use it in the solution of problems in which the numerical values of only two of the symbols are known. Thus, if the difference of potential between the ends of a wire is E volts, and if the resistance of the wire is R ohms, then the ratio $\frac{E}{R}$ will be the numerical value of the current in ampères.

Example.—The resistance of a mile of ordinary iron telegraph wire is 9 ohms, and the potential difference between its two ends is 1.25 volts. What is the magnitude of the current flowing through the wire?

$$E=1.25, \ R=9.$$

Hence $$C=\frac{E}{R}=\frac{1.25}{9}=0.14 \text{ ampère.}$$

As a general rule the equation $C=\frac{E}{R}$ is applied to the entire *circuit* traversed by the current, including the battery as well as the external wires, both of which offer a resistance to the passage of the current. Hence the symbol R includes both

the resistance of the wire (usually termed the *external resistance*) and also that of the battery (usually termed the *internal resistance*). It is better to represent these component resistances by separate symbols, and to write the equation thus—

$$C = \frac{E}{R + r},$$

where R = the external resistance, and r = the internal resistance. Since the battery has resistance, a portion of its E.M.F. will be used up in driving the current through the battery, and only the remainder of the total E.M.F. will be available for driving the current through the wire. This is rendered more evident by writing the above equation thus—

E	=	CR	+	Cr
(Total E.M.F.)		(E.M.F. used in external circuit.)		(E.M.F. used in internal circuit.)

This is represented diagrammatically in Fig. 181, where AB represents the internal resistance and BC the external resistance. AE is the total E.M.F., and Ee is the portion used up in overcoming the resistance of the cell, while BE′ represents the difference of potential between the ends of the wire. The current is represented by the tangent of the angle ECA, hence $C = \frac{Ee}{r}$, and also $C = \frac{BE'}{R}$;

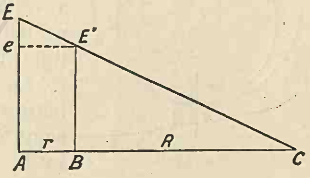


FIG. 181.

or, $$Ee = Cr, \text{ and } BE' = CR.$$

Therefore $$AE = Ee + BE' = Cr + CR.$$

Example 1.—A Grove cell has an internal resistance of 0.5 ohm, and its total E.M.F. is 1.9 volt. The poles are joined by a wire, the resistance of which is 1.5 ohm. Find the current produced and the potential difference between the terminals of the cells.

$$R = 1.5,\ r = 0.5,\ E = 1.9.$$

$$C=\frac{E}{R+r}=\frac{1.9}{1.5+0.5}=\frac{1.9}{2}=0.95 \text{ ampère.}$$

Potential difference between the ends of wire $=CR=0.95\times 1.5$
$=1.425$ volt.

Example 2.—The total E.M.F. of a battery is 10 volts. When the poles of the battery are connected by a wire a current of 2 ampères is obtained, and the potential difference of the battery poles drops to 7.5 volts. Find the resistance of the battery and of the wire.

$$C=\frac{E}{R+r}, \text{ or } R+r=\frac{E}{C}=\frac{10}{2}=5 \text{ ohms.}$$

Potential difference between the ends of wire $=CR$;

or, $7.5=2\times R$.

Hence $R=3.75$ ohms.

But $R+r=5$ ohms, therefore $r=5-3.75=1.25$ ohms.

Divided External Circuit.—*If a number of conductors are arranged with their ends in contact so that a current entering at one end has several paths open to it, they are said to be arranged in* **multiple arc** *or* **in parallel.** Fig. 182 represents a voltaic cell AB, with its poles connected together by two wires in multiple arc, the resistances of which are r_1 and r_2. The potential difference between the ends of the wires is the same in both cases; let it be denoted by E.

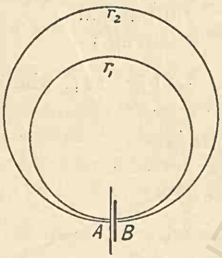


Fig. 182.

If c_1 is the current traversing the wire r_1, then $c_1=\dfrac{E}{r_1}$.

" c_2 " " " r_2, " $c_2=\dfrac{E}{r_2}$.

The total current C traversing the circuit is equal to the sum of c_1 and c_2;

$$\text{or, } C=c_1+c_2=\frac{E}{r_1}+\frac{E}{r_2}=E\left(\frac{1}{r_1}+\frac{1}{r_2}\right)=E\left(\frac{r_2+r_1}{r_1 r_2}\right)=\frac{E}{\dfrac{r_1 r_2}{r_1+r_2}}.$$

Hence *the combined resistance of two wires in multiple arc is equal to their product divided by their sum.*

Example.—The poles of an accumulator (E.M.F. $=2$ volts) are connected by two wires in multiple arc, the resistances of which are 5 ohms and 6 ohms respectively. If the internal resistance of the accumulator is 0.1 ohm, find the total current traversing the circuit.

The external resistance $=\frac{r_1 r_2}{r_1+r_2}=\frac{5\times 6}{11}=\frac{30}{11}=2.72$ ohms approximately.

The total resistance $=2.72+0.1=2.82$ ohms.

The total current $=\frac{\mathrm{E}}{\mathrm{R}}=\frac{2}{2.82}=0.708$ ampères.

Special Case of Conductors in Multiple Arc.—If the component resistances in a divided external circuit are equal to one another, then the above formula may be considerably simplified. Thus, if $r_2=r_1$, then

$$\frac{r_1 r_2}{r_1+r_2}=\frac{r_1^2}{2r_1}=\frac{r_1}{2}.$$

We may imagine the two wires to be merged into one wire of twice the cross-section of either; the resistance of this thicker wire would be half that of the thinner wire, showing that the resistance of a wire *varies inversely as its cross-section.*

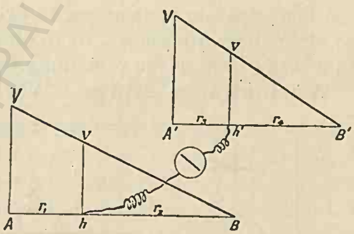


FIG. 183.

Potential Diagram of a Divided External Circuit.—Let AB and A′B′ represent the resistances of two wires which are connected together in multiple arc. The potentials at A and A′ are equal, so also at B and B′. Imagine that a terminal wire of a galvanometer is connected to a point h on the wire AB, and that the other galvanometer wire is connected to a point h' on the wire A′B′. A current will pass through the galvanometer unless h and h' are at the same potential, *i.e.* unless $hv=h'v$. Imagine that the point h' has been found such that no deflection is observed on the galvanometer. Then

$$\frac{hv}{AV} = \frac{h'v}{A'V}.$$

But, from geometry,[1] $\frac{hv}{AV} = \frac{Bh}{BA}$, and $\frac{h'v}{A'V} = \frac{B'h'}{B'A'}$.

Therefore $\frac{Bh}{BA} = \frac{B'h'}{B'A'}$. This may also be written $\frac{BA}{Bh} = \frac{B'A'}{B'h'}$.

Subtract unity from both sides, $\frac{BA}{Bh} - 1 = \frac{B'A'}{B'h'} - 1$;

or,
$$\frac{BA - Bh}{Bh} = \frac{B'A' - B'h'}{B'h'};$$

or,
$$\frac{Ah}{hB} = \frac{A'h'}{h'B'};$$

or,
$$\frac{r_1}{r_2} = \frac{r_3}{r_4}.$$

The same result may be expressed thus: $\frac{r_1}{r_3} = \frac{r_2}{r_4}$.

This result explains how it is possible, in an experiment with four separate resistances, to determine any one of them if the other three are known, or to obtain the ratio of any two of them if the ratio of the remaining two is known.

Wheatstone's Bridge.—Wheatstone's Bridge is a prac-

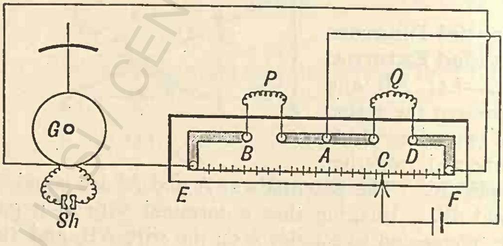


FIG. 184.—Diagram of a Wheatstone Bridge.

tical application of the theoretical result obtained in the previous section. Fig. 184 represents a simple form of the

[1] Euclid, vi. 10.

Bridge. It consists of a length of German-silver wire stretched along a board, and the ends of the wire are soldered to metal strips to which binding-screws are attached. The wire may be 50 cms. or 100 cms. long, and a wooden scale is placed under the wire to enable exact lengths of the wire to be used in experiments. The two resistances P and Q to be compared are connected to binding-screws as indicated in the diagram. The galvanometer is connected to the binding-screws at E and F. One pole of the voltaic cell is connected to A, and the other pole is connected to a long wire, the free end of which is brought into contact with various points of the German-silver wire EF. The divided circuit consists of the two paths APEC and AQFC. When the point C has been found such that no deflection is observed, then

$$\frac{P}{Q}=\frac{EC}{CF}.$$

The lengths of EC and CF are given by the wooden scale, and the ratio of their resistances is the same as the ratio of their lengths. Hence the ratio $\frac{P}{Q}$ is determined.

Experiments with the Wheatstone Bridge.—In order to determine the actual resistance (in ohms) of a wire by means of the Wheatstone Bridge, it is necessary to know the resistance of the wire with which it is compared.[1]

EXPT. 161.—(i.) *To prove that the resistance of a wire varies inversely as the cross-section.*—Measure the resistance (R_1) of 1 metre of German-silver wire (No. 28 S.W.G.), and measure its diameter (d_1) by means of a micrometer screw gauge. Measure the resistance (R_2) of 1 metre of German-silver wire (No. 22 S.W.G.), and also its diameter (d_2).

If s_1 and s_2 are the cross-sections of the wires, and r_1 and r_2 their *radii*, then $\frac{s_1}{s_2}=\frac{\pi\times r_1^2}{\pi\times r_2^2}$* $=\frac{r_1^2}{r_2^2}$.

[1] 1-ohm or 2-ohm coils may be purchased at small cost, or the student may make a rough copy of a 1-ohm coil by winding 92.3 cms. of German-silver wire (No. 28 S.W.G.) on a cotton reel, and soldering the free ends of the wire to short lengths of thick copper wire, to serve as connectors to the binding-screws.

* The area of a circle (radius r) $=\pi\times(r)^2$.

Prove that $\frac{R_1}{R_2} = \frac{s_2}{s_1} = \frac{r_2^2}{r_1^2}$.

(ii.) *To prove that the resistance of two wires in multiple arc* $= \frac{R_1 R_2}{R_1 + R_2}$ (see p. 290).—Connect in multiple arc the two German-silver wires used in the previous experiment, and measure the resistance (R) between the extreme ends. Prove that $R = \frac{R_1 R_2}{R_1 + R_2}$.

(iii.) *To prove that the resistance of a wire depends upon its temperature.*—Wind a metre of copper wire (No. 28) into a spiral, connect its ends to the bridge terminals, and fix it in a vertical position just over a Bunsen flame (taking care to adjust the spiral so that consecutive turns are not touching). Measure the resistance while hot, and repeat the measurement after the wire has been allowed to cool. Notice that the resistance is greater when hot.

GROUPING OF CELLS

The various methods of grouping cells together so as to form a battery have already been described in Chapter XVII. (p. 249), and are there classified under three headings—(i.) *in series*, (ii.) *in parallel*, and (iii.) *in multiple arc.*

Cells in Series.—If n cells are connected together in series, and if E and r are the E.M.F. and internal resistance of each cell, then

$$\text{The total E.M.F.} = nE.$$
$$\text{,, internal resistance} = nr.$$

Then, by Ohm's Law, $$C = \frac{nE}{R + nr} \qquad (1)$$

Fig. 185 represents a battery of two cells in series. The continuous and the thick dotted lines are the potential diagrams when the circuit is open and closed respectively. The lengths AB and BC represent the internal resistances of the cells, and CD represents the external resistance. AV (or CV′) is the

total E.M.F. The current is represented by the ratio $\frac{AV}{AD}$ (*i.e.* by $\tan\theta$). Before the circuit is closed the potential difference between the terminals is CV′, but as soon as the circuit is closed the potential difference at the terminals falls to Cv. The remainder of the total E.M.F. (viz. V′v) is used up in overcoming the internal resistance of the two cells and

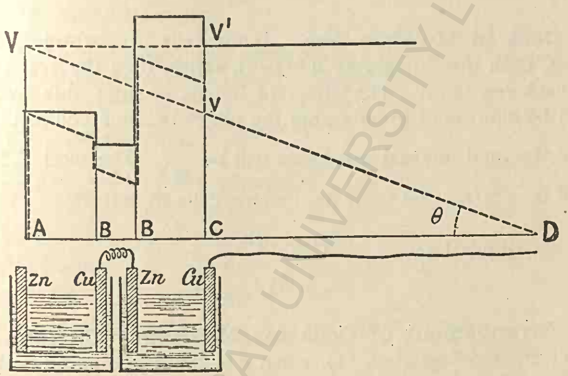


FIG. 185.—Potential diagram of a simple circuit containing two cells in series.

the resistance of the connecting wire BB. (The latter is usually very small, and may be disregarded.) In this case equation (1) becomes $C = \frac{2E}{R + 2r}$.

Special Case.—Suppose that one of the n cells is accidentally reversed, so that it tends to send a current in the opposite direction. What will be the final result? There are $n - 1$ cells tending to send a current in one direction, and with an E.M.F. $= (n - 1)E$, while there is one cell tending to reverse the current with an E.M.F. $= E$. The resultant E.M.F. $= (n - 1)E - E = (n - 2)E$.

Hence, by Ohm's Law, $C = \frac{(n - 2)E}{R + nr}$.

Cells in Parallel.—If m cells are connected together in parallel, the E.M.F. will be the same as that of one cell. The

arrangement will be equivalent to one large cell, the plates of which are m times as large as those of a single cell, hence the internal resistance will $= \frac{r}{m}$ (where $r =$ the resistance of a single cell).

By Ohm's Law,
$$C = \frac{E}{R + \frac{r}{m}} \quad . \quad . \quad . \quad . \quad (2)$$

Cells in Multiple Arc.—If the cells are arranged in m rows, each row containing n cells in series, then the resistance of each row is nr. The effect of having m rows side by side will be equivalent to enlarging the plates of each cell m times, and the total internal resistance will be $\frac{nr}{m}$. The total E.M.F. will be nE (*i.e.* the same as n single cells in series).

By Ohm's Law,
$$C = \frac{nE}{R + \frac{nr}{m}} \quad . \quad . \quad . \quad . \quad (3)$$

Arrangement of Cells for Maximum Current.—It is clear, from equation (1), when r is small compared with R, that the current obtained is approximately proportional to the number of cells used. But if R is small compared with r, then the current is scarcely increased by an increase in the number of cells, since the total resistance $(R + nr)$ will be increased almost in the same proportion as the E.M.F.; in this case it is advantageous to connect the cells in multiple arc so as to reduce the internal resistance. It can be proved, by mathematics, that a maximum current is obtained when the cells are so arranged that the internal resistance is equal to the external resistance.

Example 1.—The poles of a battery of three cells (each having an internal resistance $= 2$ ohms, and an E.M.F. $= 1$ volt) are joined by a wire having a resistance of 0.5 ohm. Find the magnitude of the current (i.) with three cells in series, (ii.) with two cells in series, and (iii.) with three cells in multiple arc.

(i.) $C = \frac{nE}{R + nr} = \frac{3}{0.5 + 6} = \frac{3}{6.5} = 0.46$ ampère.

(ii.) $C=\frac{nE}{R+nr}=\frac{2}{0.5+4}=\frac{2}{4.5}=0.44$ ampère.

(iii.) $C=\frac{E}{R+\frac{r}{n}}=\frac{1}{0.5+\frac{2}{3}}=\frac{1}{1.16}=0.86$ ampère.

Evidently two cells will give approximately the same current as three cells, and a much greater current is obtained if the three cells are in parallel.

Example 2.—Repeat the calculations in Example 1, but making the external resistance much greater. Let $R=20$ ohms.

(i.) $C=\frac{3}{20+6}=\frac{3}{26}=0.115$ ampère.

(ii.) $C=\frac{2}{20+4}=\frac{2}{24}=0.083$ ampère.

(iii.) $C=\frac{1}{20+\frac{2}{3}}=\frac{1}{20.16}=0.049$ ampère.

(iv.) With a single cell, $C=\frac{1}{20+2}=\frac{1}{22}=0.045$ ampère.

In this case it is evidently an advantage to increase the number of cells in series, and a single cell gives almost the same current as several cells connected in parallel.

EXPT. 162.—(i.) Connect two Daniell cells in series, and connect the terminals of this battery to the low resistance coil of a tangent galvanometer by means of thick copper wire. Observe the deflections in each of the following cases :—

(*a*) With the two cells in series (deflection $=\theta_1$).
(*b*) With a single cell (deflection $=\theta_2$).
(*c*) With two cells in parallel (deflection $=\theta_3$).

Observe that $\tan\theta_1$ approximately $=\tan\theta_2$, and that $\tan\theta_3$ is considerably greater than either $\tan\theta_1$ or $\tan\theta_2$.

(ii.) Repeat the previous experiment, but use the higher resistance coil of the galvanometer, and perhaps increase the external resistance still more by inserting a length of thin German-silver wire into the circuit. If the

deflections are denoted by θ_1, θ_2, and θ_3 respectively, observe that $\tan \theta_1$ approximately $= 2 \tan \theta_2$, and that $\tan \theta_3$ approximately $= \tan \theta_2$.

Chief Points of Chapter XXI

Electro-magnetic Units.—(i.) *Electromotive Force.*—Unit potential difference exists between two points when 1 erg of work has to be done in order to convey unit quantity of electricity between the two points.

(ii.) *Resistance.*—A conductor has unit resistance when unit potential difference between its ends causes a current of unit strength (p. 275) to flow through it.

Practical Units.—(i.) *Current.*—The **Ampère** $= \frac{1}{10}$ electro-magnetic unit. (ii.) *Electromotive Force.*—The **Volt** $= 10^8$ electro-magnetic units. (iii.) *Resistance.*—The **Ohm** $= 10^9$ electro-magnetic units.

Practical Application of Ohm's Law.—By giving to the symbols C, E, and R their numerical value in *practical* units, the expression $C = \frac{E}{R}$ becomes a correct mathematical equation. The symbol R refers to the *total* resistance in the circuit, hence Ohm's Law is more completely expressed by the equation $C = \frac{E}{R+r}$ (where R = external resistance, and r = internal resistance).

Divided External Circuit.—If two wires, having resistance R_1 and R_2 respectively, are joined in multiple arc, the combined resistance is given by the formula, $R = \frac{R_1 R_2}{R_1 + R_2}$.

Wheatstone's Bridge is an appliance for comparing any two resistances.

Grouping of Cells.—(i.) *In Series.*—If n cells (each having an E.M.F. = E, and internal resistance $= r$) are joined together in series, and if R = external resistance, then $C = \frac{nE}{R + nr}$.

(ii.) *In Parallel.*—If m cells are joined together in parallel, then $C = \frac{E}{R + \frac{r}{m}}$.

(iii.) *In Multiple Arc.*—If mn cells are joined together in m rows, each containing n cells in series, then $C = \frac{nE}{R + \frac{nr}{m}}$.

QUESTIONS ON CHAPTER XXI

1. Two galvanic cells are made by dipping (1) plates of zinc and platinum into a beaker of dilute sulphuric acid, and (2) plates of zinc and copper into another beaker containing the same liquid. The plates can be connected by copper wires. Explain with diagram how the two cells may be connected in series so as to (1) strengthen, (2) weaken, the current produced by one of them. (1898.)

2. It is intended to set up 100 Grove cells in series, but by mistake 10 cells are arranged in opposition to the rest. What is the relation of the potential difference of the terminals on open circuit to that which would have been obtained if the mistake had not been made? (1892.)

3. Find the total resistance in a circuit in which an E.M.F. of 8 volts gives a current of 1.5 ampères. (Coll. Precep. Prelim. 1893.)

4. The E.M.F. between the poles of a battery is 12 volts when the external circuit is "open," and 10 volts when it is closed by a resistance such that a current of 6 ampères is passing. Find the resistance of the battery. (C.U.L.S. 1895.)

5. The zinc pole of a Daniell cell being joined to the platinum pole of a Grove cell, the other poles are connected up with a tangent galvanometer, and produce a current of 0.5665 ampère; the zinc pole of one is next joined to the zinc pole of the other, and the +ve poles are connected with the galvanometer by the same wires as before, whereby a current is produced whose value is 0.0875 ampère. Deduce the ratio of the E.M.F. of the two cells.

(Coll. Precep. Cert. 1890.)

6. Four cells, each of 2 volts E.M.F., and 0.1 ohm internal resistance, are used to send a current through a wire of resistance 0.1 ohm. Compare the currents in the wire when the cells are (i.) in series, (ii.) in two parallel rows, each with two in series, (iii.) all parallel.

(Lond. Matric. 1896.)

7. A galvanometer connected (*a*) in series, (*b*) in parallel, with a resistance of 3 ohms and a battery of constant E.M.F. and negligible resistance, indicates currents which are in the ratio of 3 to 4. Find the resistance of the galvanometer. (C.U.L.S. 1898.)

8. A wire is formed into a circle, 1 foot in diameter, and two points, A and B, a quarter of the circumference apart, are connected to the poles of a battery of E.M.F. 2 volts, and resistance 5 ohms. If 1 foot of the wire have a resistance of 6 ohms, find the current in the battery and in the two parts of the wire. (Lond. Matric. 1890.)

9. Explain the principle of the Wheatstone Bridge, and describe briefly how it is used in order to compare two resistances.

CHAPTER XXII

THERMAL AND CHEMICAL EFFECTS

Apparatus required.—Two large Bunsen cells. Platinum wire (No. 32 S.W.G.). Thermometer. Two calorimeters (Fig. 186). Burette. Dilute H_2SO_4 (1 in 8). Solution of copper sulphate. Apparatus for electrolysis of water (Fig. 187). Water voltameter. Copper voltameter. Tangent galvanometer. Nitric acid. Balance and weights.

THERMAL EFFECTS

Conversion of Electrical Energy into Heat.—Unit potential difference has already been defined as that which requires the expenditure of unit work in order to convey unit quantity between two points, the potentials of which differ by unity. If the unit quantity is forcibly conveyed from lower to higher potential (*i.e.* in opposition to the electric forces) the work has to be done by some external agency; but if it proceeds in the opposite direction (*i.e.* in obedience to the electric forces), then unit work will be done *by* the electric forces. In a simple electrical circuit this work reappears in the form of *heat.*

If Q coulombs of electricity traverse a wire, between the ends of which there is a potential difference of E volts, then the measure of the work done in the wire is $(Q \times E)$ practical units. (This unit of work is called the *Joule.*[1])

---

[1] James Prescott Joule (1818-1889), born at Salford.

If this is expressed in electro-magnetic units, since 1 coulomb $=\frac{1}{10}$ electro-magnetic unit of Quantity, and 1 volt $=10^8$ electro-magnetic units of P.D., the work done $=QE(\frac{1}{10}\times 10^8)$ ergs $=QE \times 10^7$ ergs. Hence 1 Joule $=10^7$ ergs.

Since $Q=Ct$, the work done $=ECt$ Joules.

But, by Ohm's Law, $E=CR$.

Hence ECt Joules $=C^2Rt$ Joules $=(C^2Rt\times 10^7)$ ergs.

This is an expression for the quantity of work which reappears as *heat* in a simple circuit.

Experiments on the Generation of Heat in a Simple Circuit.—From the theoretical results deduced in the previous section the amount of heat generated depends both upon the current and the resistance.

EXPT. 163.—Connect two large Bunsen cells in series. Connect the poles, by means of thick copper wires, to the ends of a short piece of platinum wire (No. 32 S.W.G.). Observe how the wire is heated, and perhaps even glows. If the wire is too long it will not glow, since the total resistance is too great to allow sufficient current for the experiment; the resistance may be reduced either by shortening the wire, or by reducing the resistance of a portion by immersing it in a vessel of cold water, when the remaining portion will glow brightly.

Since the battery has internal resistance heat will also be generated in this portion of the circuit.

EXPT. 164.—Immerse a thermometer in the acid of one of the cells, and read the temperature of the liquid. Connect the poles by means of a short thick wire, and allow the current to continue for a short time. Observe how the temperature of the battery gradually rises.

Joule's Law.—The heat generated in a simple circuit is proportional (i.) to the square of the current, (ii.) to the resistance, (iii.) to the time during which the current continues. The general principle of the apparatus which Joule used in the experimental proof of this law may be understood by reference to Fig. 186. The ends of an open coil of thin German-silver wire are connected to thick copper wires passing through a wide cork fitting into

the top of a thin metal vessel (made of sheet brass or copper and called a *calorimeter*) containing water. A thermometer is fixed through the centre of the cork so that its bulb is immersed in the water. In order to prevent the current from leaking through the water instead of traversing the wire, it is advisable to coat the surface of the wire with a thin insulating layer of shellac by dipping the wire into shellac varnish and heating it in an air-bath to 140° C.

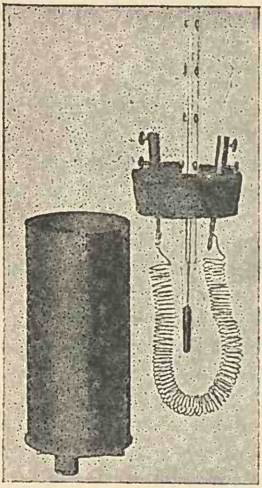


FIG. 186.—Apparatus for measuring heat developed in a wire.

EXPT. 165.—(i.) Pour a measured quantity of water into the calorimeter sufficient to cover the German-silver wire. Read the thermometer. Complete the circuit, which includes a tangent galvanometer and one Bunsen cell. Note the time. Read the deflection, and allow current to pass until the temperature has risen, say, 3° C. Occasionally shake the calorimeter slightly so as to allow the water to become uniformly heated. Note the time at the instant of breaking the circuit. Repeat the experiment, using two cells, and allowing the current to pass for the same period of time as before.

$$\text{Prove that } \frac{\text{Rise of temp.}_1}{\text{Rise of temp.}_2} = \frac{(\tan\,\theta_1)^2}{(\tan\,\theta_2)^2}.$$

(ii.) Replace the water by the same volume of fresh cold water. Use one cell only, and repeat Expt. (i.), but allowing the current to proceed for twice the length of time. Observe that the rise in temperature is twice as great as before, or

$$\frac{\text{Rise of temp.}_1}{\text{Rise of temp.}_3} = \frac{\text{time}_1}{\text{time}_3}.$$

(iii.) Connect together two calorimeters of the same size in series, but let the spiral in one of them be *twice as long* as that in the other. Pour equal volumes of cold water into the calorimeters, and observe the rise in temperature of the water in the two vessels after a current has passed for a short time. Notice that the rise in temperature due to the longer spiral is twice as great as that due to the shorter spiral. Hence the heat generated is proportional to the resistance.

The relationship between the heat generated and the resistance may be well shown by passing a fairly strong current through a chain the alternate links of which are made of thin platinum and silver wire (both of same diameter). Platinum has a much higher resistance than silver, and more heat will therefore be generated in the platinum than in the silver, with the result that the former will glow brightly while the latter will remain comparatively cool.

The amount of heat generated is measured in terms of a unit called the *calorie*.[1] If W = weight of water used, and T = rise in temperature,

$$\text{Heat generated} = (W \times T) \text{ calories.}$$

By elaborate experiments Joule has determined that the energy equivalent to one calorie, expressed in units of work, is (4.2×10^7) ergs.

But the work done in a simple electric circuit $= (C^2Rt \times 10^7)$ ergs.

Hence the number of heat units generated in a simple circuit $= \left(\dfrac{C^2Rt \times 10^7}{4.2 \times 10^7}\right) = \dfrac{C^2Rt}{4.2}$ calories.

This result indicates that the measurement of the heat developed in a wire of known resistance affords a means of measuring the strength of the current traversing the wire. The amount of heat generated in the calorimeter, $(W \times T)$, is equated to $\dfrac{C^2Rt}{4.2}$, thus

$$W \times T = \frac{C^2Rt}{4.2},$$

or,

$$C = \sqrt{\frac{W \times T \times 4.2}{R \times t}}.$$

[1] The *calorie* is the amount of heat required to raise 1 gram of water 1° C.

The essential data are (i.) the resistance of the wire, (ii.) the weight of water in calorimeter, (iii.) the rise in temperature, and (iv.) the time.

CHEMICAL EFFECTS OF THE ELECTRIC CURRENT

Liquid Conductors.—The passage of a current through *mercury* is similar in every respect to the passage of a current through a solid metal conductor—heat is developed in the mercury, but no other change is evident. But when the current traverses other liquids (*e.g.* acids, solutions of chemical salts, etc.) they undergo chemical change. *Liquids which undergo chemical change when traversed by an electric current are termed* **Electrolytes**, and they are said to undergo **Electrolysis.**

EXPT. 166.—(i.) Connect two short lengths of platinum wire to copper wires attached to the poles of a battery. Dip the platinum wires into a beaker of dilute sulphuric acid. Notice how bubbles of gas are liberated from the wires.

In a subsequent experiment it will be found that these two gases are hydrogen and oxygen—the constituent elements of water—and that the oxygen is being liberated from the wire connected to the + ve pole of the battery, and the hydrogen from that connected to the − ve pole. The water is undergoing the process of electrolysis.

The ends of the wires connected to the battery are termed **electrodes** ; that by which the current enters the electrolyte is termed the **anode**, and that by which it leaves is termed the **kathode**. The elements (or group of elements) liberated at the anode and kathode are termed the **anion** and **kation** respectively.

(ii.) Dip the platinum wires into a solution of copper sulphate. Allow the current to pass for a few moments, and observe how the kathode becomes coated with a layer of copper (having a characteristic salmon-pink colour).

Electrolytes.—Sulphuric acid (H_2SO_4) and hydrochloric acid (HCl) are typical examples of acid electrolytes. When the hydrogen contained in the acid is replaced by a metal, then a *salt* is produced ;

copper sulphate ("blue vitriol," $CuSO_4$), sodium chloride ("common salt," NaCl), and sodium sulphate ("Glauber's salts," Na_2SO_4) are examples of chemical *salts*. Perfectly pure water is not an electrolyte (in fact, it can scarcely be called a conductor), but if it is acidulated with sulphuric acid it becomes a conductor and undergoes electrolysis.

Electrolysis of Water.—A suitable form of apparatus (Fig. 187) may be made in the following manner:—Cut the tube off a glass funnel and close the lower end by means of a cork, through which pass two platinum wires. To the upper end of each wire weld a short strip of platinum foil, and solder the lower end to a piece of thick copper wire. Pour melted paraffin wax into the funnel as far as the lower edge of the foil. Select two test-tubes of exactly the same size.

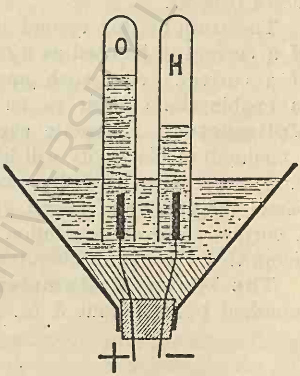


FIG. 187.—Apparatus for electrolysis of water.

EXPT. 167.—Nearly fill the funnel with dilute sulphuric acid; fill the test-tubes with a similar acid, and invert them over the platinum strips. Connect the copper wires to the terminals of a Bunsen battery (of at least two cells). Notice how the kation accumulates twice as rapidly as the anion. Break the circuit, and remove the test-tubes (carefully closing the end with the thumb before removing it from the acid). Verify that the kation is hydrogen, and that the anion is oxygen.

The electrolysis of water may be represented thus:—

H_2O		H_2	+	O.
Water	is decomposed into	2 vols. *Hydrogen*	and	1 vol. *Oxygen.*

Faraday's Laws of Electrolysis.—Faraday fully investigated the phenomena of electrolysis, and deduced the following laws:—

(i.) *The amount of chemical action is equal at all points of a circuit.* Thus, if a current successively traverses two appliances for the electrolysis of water, the amount of chemical action will be the same in each, whatever the relative size of the appliances may be.

(ii.) *The amount of an element* (or *ion*) *liberated is proportional to the strength of the current, and to the time during which it flows.*

The truth of this second law enables the chemical action of a current to be used as a means of measuring the strength of a current. Any such appliance which is so devised as to enable the current to be thereby measured is termed a **Voltameter.** Elaborate experiments have determined that 1 coulomb of electricity will liberate 0.1155 c.c. hydrogen and 0.0577 c.c. oxygen (if the gases are collected together in one vessel the volume of mixed gases will be 0.1732 c.c.); when a current traverses a solution of copper sulphate it has been found that 1 coulomb liberates 0.0003281 gm. copper.

The Water Voltameter (Fig. 188).—Procure a wide-mouthed bottle (about 8 oz. size) fitted with a cork stopper. Pass two stout copper wires through the cork at points about 2 cms. apart. Solder to the lower end of each copper wire a short length of platinum wire, to the lower end of which is welded a piece of platinum foil (about 3 cms. × 1 cm.). Protect the soldered joints with varnish. Through a third hole in the cork pass a piece of narrow glass tubing, the upper end of which is bent at right angles. The liberated gases may be collected in a calibrated burette inverted in a dish of water. Pour sufficient dilute sulphuric acid into the bottle to cover the strips of foil. Insert the cork and paint it with melted paraffin wax to

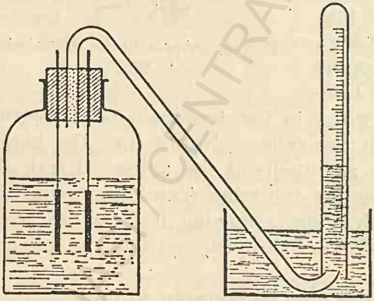


FIG. 188.—Water voltameter.

prevent any possible leakage. Care should be taken not to send too strong a current through the voltameter, since a hot platinum wire will ignite the explosive mixture of hydrogen and oxygen.

EXPT. 168.—Connect a tangent galvanometer and a water voltameter in series with a battery of two Bunsen cells. The current may be controlled, if necessary, by inserting a short length of German-silver wire in the circuit. Note the time at the instant of completing the circuit. Read the galvanometer at the end of each minute. Break the circuit when a considerable volume of mixed gases has been obtained, and note the time at the instant of breaking the circuit. Divide the volume (V) of gas by the time (t seconds).

$$\frac{V}{t} = \text{volume of mixed gases liberated in 1 second.}$$

But 1 ampère liberates 0.1732 c.c. of mixed gases in 1 second.

Hence $$\text{Current} = \frac{V}{t \times 0.1732} \text{ ampères.}$$

The Constant of a Tangent Galvanometer.—It has been explained (on p. 268) that the current traversing the coil of a tangent galvanometer is *proportional* to the tangent of the angle of deflection ($\tan\theta$). *The numerical quantity by which* $\tan\theta$ *must be multiplied in order to give the numerical value of the current (in ampères) is termed the* **Constant** *of the galvanometer.* If this constant quantity is denoted by the symbol k, then the fundamental formula for the galvanometer may be written, $C = k \times \tan\theta$.

The value of k may be approximately determined by making a simple measurement of the current (by means of a water voltameter) and taking the average value of $\tan\theta$ during the passage of the current. All the required data have therefore been obtained in Expt. 168, and it is only necessary to apply the formula

$$k = \frac{C}{\tan\theta} = \frac{V}{t \times 0.1732 \times \tan\theta}.$$

This value of k may be verified by measuring the current by means of the copper voltameter (Expt. 169).

The Copper Voltameter.—The copper voltameter de-

pends upon the principle that copper is deposited on the kathode when a current traverses a solution of copper sulphate. The apparatus may be made in the following manner:—Cut two pieces of pure copper foil to the shape shown in Fig. 189 to serve as the electrodes, making the square surface of the kathode smaller than the anode. Make a 10-15 per cent solution of copper sulphate, and add 5 c.c. of strong sulphuric acid to each litre of the solution. Suspend the electrodes in a beaker of this solution from two copper wires resting on the edges of the beaker. Attach a binding screw to the end of each wire.

FIG. 189.

EXPT. 169.—Clean both copper plates by immersing them for a few seconds in strong nitric acid, wash thoroughly under the tap, rinse with distilled water, dry quickly in a water bath, and weigh separately when cold. Connect up a tangent galvanometer and the voltameter in series with a single Bunsen cell. Note the time at the instant of completing the circuit. Read the deflection at the end of every two minutes, and allow the current to proceed for twenty to thirty minutes. Note the time at the instant of breaking the circuit. Quickly wash the copper electrodes, dry them and weigh separately. Determine the *increase* in weight of the kathode, and observe that the *loss* in weight of the anode is practically the same amount.

If W = increase in weight of kathode, and t = duration of experiment in seconds,

$$\frac{W}{t} = \text{weight of copper deposited in 1 second.}$$

But 1 ampère deposits 0.0003281 gm. copper in 1 second.

Hence $$\text{Current} = \frac{W}{t \times 0.0003281} \text{ ampères.}$$

Theory of Electrolysis.—The theoretical explanation of

the electrolysis of water is not so simple as would appear from the equation

$$H_2O = H_2 + O,$$

since this does not take into consideration the presence of the sulphuric acid which is essential to the experiment. The explanation of the simple voltaic cell (p. 242) is directly applicable to the electrolysis of water; the potential difference set up between the electrodes causes a breaking-up of the H_2SO_4 molecules, thus

$$H_2SO_4 = SO_4 + H_2.$$

The hydrogen is drawn towards the kathode and is there liberated, while the *sulphion* (SO_4) is drawn towards the anode where it acts upon a molecule of water, thus

$$SO_4 + H_2O = H_2SO_4 + O,$$

and in this manner re-forms sulphuric acid and liberates oxygen.

The student will remember that the accumulation of hydrogen on the copper plate of a simple voltaic cell causes *polarisation* (p. 240), and an opposing E.M.F. (or *back* E.M.F.) is thereby set up, since the hydrogen is a readily-oxidizable element, and behaves in a similar manner to the zinc plate of the simple voltaic cell.

In the water voltameter this back E.M.F. is set up. If E = total E.M.F. of battery, and E' = back E.M.F. in the voltameter, the resultant E.M.F. for the complete circuit is $E - E'$, and the magnitude of the current obtained depends directly upon the magnitude of this resultant E.M.F. If $E' = E$ then no current will be obtained. In the case of a water voltameter $E' = 1.47$ volts, so that the E.M.F. of the battery must be greater than this in order to electrolyse water. This explains why a single Bunsen cell (E.M.F. = 1.9 volts) will electrolyse water, and why it is necessary to use at least two Daniell cells (E.M.F. = 1.07).

If the dilute acid is replaced by copper sulphate, copper is liberated at the kathode instead of hydrogen, but the changes at the anode are the same as in the water voltameter. Since copper is not so readily oxidized as hydrogen, it follows that the back E.M.F. in this case is less than that of the water voltameter. This holds good if platinum electrodes are used, but the conditions are altered if copper electrodes

are used; oxygen is not necessarily set free, since it may combine with the copper anode and form copper oxide.

$$Cu + O = CuO.$$

In the presence of sulphuric acid, the CuO will dissolve to form copper sulphate.

$$CuO + H_2SO_4 = CuSO_4 + H_2O.$$

The extent of this reaction depends upon the amount of acid present, but it is assured if the acid is added to the original electrolyte. Moreover, this reaction is the more important since the back E.M.F. will no longer exist, for the chemical energy absorbed in removing the copper from the solution at the kathode is restored by the solution of an equal weight of copper at the anode. It will also be observed that the re-formation of $CuSO_4$ at the anode ensures the strength of the solution being maintained.

The student will notice an analogy between these phenomena of electrolysis and the movement of +ly and −ly charged conductors in an electrostatic field of force. A modern theory maintains that in an electrolytic cell, the kation has a +ve charge and proceeds along the lines of force from higher to lower potential, and that the anion has a −ve charge and proceeds in the opposite direction.

Further Examples of Electrolysis.—The student will have observed that, in the electrolysis of sulphuric acid (or, as it may be termed, *hydrogen* sulphate) and of copper sulphate, the hydrogen and the copper traverse the electrolytic cell in the same direction. This statement holds good in the electrolysis of all metallic salts, and it is an invariable rule that *the metallic ion always travels with the current.*

Electroplating.—The commercial process of depositing a thin layer of a metal by electrolysis on the surface of a baser metal (*e.g.* German silver) is termed *electroplating.* The metal articles which are to be electroplated are suspended in a bath of a suitable electrolyte, and are so connected to a battery (or dynamo) as to serve as the *kathode* when the circuit is complete. The following table gives the main details in the processes of copper-plating, nickel-plating, electro-silvering, and electro-gilding.

ANODE.	ELECTROLYTE.
Copper.	Solution of copper sulphate.
Nickel.	Solution of nickel-ammonium sulphate and ammonium sulphate.
Silver.	Solution of double cyanide of silver and potassium.
Gold.	Solution of double cyanide of gold and potassium.

CHIEF POINTS OF CHAPTER XXII

Conversion of Electrical Energy into Heat.—When an electric current traverses a simple circuit the work done by the electric forces reappears in the form of heat.

Heat is generated wherever resistance is offered to the passage of the current, and it will therefore appear inside the battery as well as in the external circuit.

Joule's Law.—The heat generated in a simple circuit is proportional (i.) to the square of the current, (ii.) to the resistance, and (iii.) to the time during which the current continues.

The heat may be measured by observing the rise in temperature of a measured volume of water. One unit of heat (the *Calorie*) will raise the temperature of 1 gram of water through 1° C.

The work done in the circuit $= C^2Rt$ Joules $= (C^2Rt \times 10^7)$ ergs.

The mechanical equivalent of 1 calorie $= (4.2 \times 10^7)$ ergs.

Hence the heat generated $= \dfrac{C^2Rt}{4.2}$ calories.

This result indicates how the strength of the current may be determined by measuring the amount of heat generated in the circuit.

Chemical Effects.—Liquids which undergo chemical change when traversed by an electric current are termed *Electrolytes*, and they are said to undergo *Electrolysis*. The terminals dipping into the electrolyte are termed *electrodes*; the *Anode* is the terminal by which the current enters the electrolyte, and the *Kathode* is the terminal by which the

current leaves the electrolyte. The *Anion* and *Kation* are the elements (or groups of elements) liberated at the anode and kathode respectively.

Electrolysis of Water.—*Hydrogen* and *Oxygen* are the kation and anion respectively, and are liberated in the proportion of two to one by volume.

Faraday's Laws of Electrolysis.—(i.) *The amount of chemical action is equal at all points of a circuit.* (ii.) *The amount of an element* (or *ion*) *liberated is proportional to the strength of the current, and to the time during which it flows.*

The Water Voltameter is a form of apparatus in which the hydrogen and oxygen set free by the electrolysis of water are collected together in a measuring vessel. By Faraday's second law the current strength may be calculated from the volume of mixed gases liberated in a given time.

The Constant of a Tangent Galvanometer is the numerical quantity by which tan θ must be multiplied in order to give the strength of the current (in ampères). If the constant is denoted by the symbol k, then $C = k \tan \theta$.

The Copper Voltameter is a form of apparatus in which the current strength may be calculated from the weight of copper deposited on the kathode in a given time.

Theory of Electrolysis.—The electrolysis of water (acidulated with H_2SO_4) is supposed to take place in two stages, (i.) $H_2SO_4 = SO_4 + H_2$, (ii.) $SO_4 + H_2O = H_2SO_4 + O$.

The hydrogen liberated at the kathode sets up a *back E.M.F.* equal to 1.47 volt; for this reason water cannot be electrolysed by means of a single Daniell cell (E.M.F. = 1.07 volt). A much smaller back E.M.F. is set up when the acidulated water is replaced by a solution of copper sulphate; if the anode is a copper plate there is no back E.M.F.

Direction of Movement of Ions.—The metallic ion always travels *with* the current.

Electroplating is the process of depositing a thin layer of one metal upon another by means of electrolysis.

Questions on Chapter XXII

1. Explain why, when a sufficiently strong current passes through an incandescent lamp, the lamp becomes hot, while the wires which lead the current to it are comparatively cold. (1894.)

2. A current flows through a copper wire, which is thicker at one end than at the other. If there is any difference either (1) in the strength of the current at, or (2) in the temperature of, the two ends of the wire, state how they differ from each other, and why. (1888.)

3. The current from a voltaic battery is passed at the same time through a thin wire and through dilute sulphuric acid, connected in series. What will happen to the wire and to the dilute acid; and what change (if any) will be produced in each case by reversing the battery connections, so as to alter the direction of the current through the wire and liquid? (1887.)

4. State Joule's law for the heating effect of a current, and explain how it can be experimentally illustrated. (C.U.L.S. 1898.)

5. Find how many grams of water would be heated 1° C. by immersing in it a wire coil whose resistance is 7 ohms, and passing a current of 0.3 ampère for ten minutes, supposing all the heat communicated to the water. (Coll. Precep. Prel. 1893.)

6. State Faraday's Laws of Electrolysis. (Lond. Matric. 1897.)

7. What will occur when you connect (*a*) one Daniell cell, (*b*) two Daniell cells, with a water voltameter? (C.U.L.S. 1898.)

8. Plates of copper and of platinum are dipped into a solution of copper sulphate, and a current is passed through the cell from the copper to the platinum. Describe the effects produced; also what happens when the current is reversed. (1892.)

9. A number of cells formed of plates of zinc and platinum, immersed in dilute sulphuric acid, are to be connected in a circuit, so that the platinum of each cell is in contact with the zinc of the next. What effect, if any, would be produced on the current if, by mistake, one cell was made up with two platinums instead of with one platinum and one zinc plate?

10. An electric current (which is the same in all parts of the trough) flows horizontally in a trough filled with copper sulphate. A rod of copper is then supported horizontally in the trough, with its length parallel to the direction in which the current is flowing. How will the rod be affected by the current? (1893.)

11. Two pieces of lead connected by wires with the poles of a voltaic battery are dipped into a solution of lead acetate. State what happens, and show how to prove your statements experimentally. (1895.)

12. How may electrolysis be used to test the accuracy of an instrument designed to measure a current in ampères?

13. Two wires of the same size and length, one of copper and the other of iron, are joined in series and connected to the poles of a battery. In this case the iron wire becomes hotter than the copper. The two wires are then connected in parallel to the same battery, and the copper is observed to become hotter than the iron. Explain these observations. (1904.)

14. A current is sent through a piece of fine wire by a voltaic cell, the resistance of which is very small compared with that of the wire. How will the heat produced be altered if the length of the wire is halved? (1904.)

CHAPTER XXIII

ATTRACTION AND REPULSION OF LINEAR CURRENTS—ELECTRO-MAGNETIC INDUCTION

Apparatus required.—Apparatus as represented in Figs. 191 and 194. Coils and flat spirals of wire. Mirror galvanometer. Small bar-magnet. Bunsen cells.

Behaviour of a Linear Current in a Magnetic Field.—If A (Fig. 190, i.) represents the cross-section of a wire conveying a current *down* through the paper, and *n* a single north-seeking pole, the latter will tend to move round A in a clockwise direction to *n'*. But if *n* is fixed and A free to move, then A will move in such a manner that it will subsequently occupy the same relative position with respect to *n* as would be the case if A were fixed and *n* were free to move; hence A will move towards A' (Fig. 190, ii.). This effect, being continuous so long as the current lasts, will cause A to rotate round *n*, and it can be experimentally verified with the apparatus shown in Fig. 191.

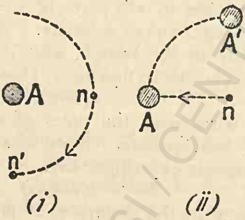


Fig. 190.

G is a glass tube (20 cms. × 4 cms.) closed at both ends with corks. A cylindrical bar-magnet is fixed through the centre of the lower cork with its north-seeking pole uppermost and projecting a short distance into the tube; a copper wire is also fixed through the same cork. A thick wire bent into the form of a hook is passed through the centre of the upper cork,

and supports a thin wire the lower end of which dips into the mercury (H).

EXPT. 170.—Take special precautions that the surface of the mercury is quite clean. Pass a strong current *down* the wire, and observe the direction of rotation. Reverse the direction of the current and observe how the rotation is reversed.

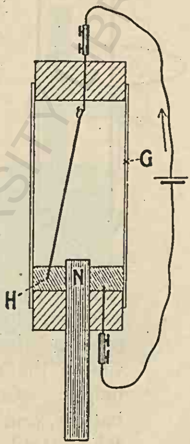


FIG. 191.—Apparatus for showing rotation of a linear current round a magnet-pole.

This movement of the current is due to the field of the magnet, and at any instant the direction of motion is perpendicular to the direction of the lines of magnetic force and also to the direction of the current. The following rule, due to Professor Fleming, will be found useful in determining the direction of motion of a linear current when placed in a magnetic field:—*Hold the thumb and first finger of the left hand as fully extended as possible, and bend the second finger at right angles to the palm. If the first finger represents the direction of the lines of force, and the second finger that of the current, then the thumb will indicate the direction of motion* (Fig. 192).

Motion of a Linear Current in the Field due to another Linear Current.—Let AB (Fig. 193) be a fixed wire conveying a current from A to B. The direction of the magnetic force at P, due to the current in AB, will be downwards and at right angles to the paper. If a wire CD, which is free to move and conveying a current from C to D, passes through P and is parallel to AB, then the *left-hand rule* deduced above indicates that CD will move towards AB; in other words, CD will be *attracted* by AB. If the current in

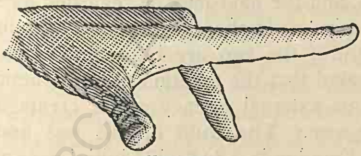


FIG. 192.

CD is reversed then *repulsion* will take place. Hence, according to theory, *two parallel wires conveying currents in the same direction will attract each other, and if the currents are in opposite directions they will repel each other.*

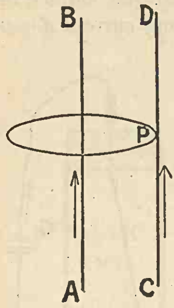


FIG. 193.

EXPT. 171.—Bend a copper wire into a rectangular form ABCD (Fig. 194) and solder the ends to two lengths of tinsel, the upper ends of which are soldered to two copper wires passing through the cork X. Clamp the cork at a convenient height. Connect the wires to the terminals of a battery, and include in the circuit a length of free wire EF. Hold EF near to and parallel to the sides of the suspended rectangle, and verify attraction in one case and repulsion in the other.

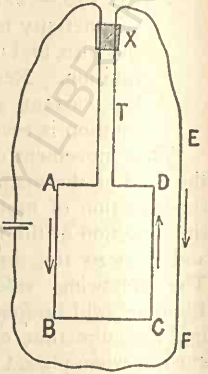


FIG. 194.—Apparatus to show attraction and repulsion of linear currents.

ELECTRO-MAGNETIC INDUCTION

Faraday's Discovery of an Induced Current.—An electric current traversing a wire creates a magnetic field in the space surrounding the wire, and the field may be regarded as a *magnetic whirl* round the wire. If the creation of a current creates a magnetic field, and if the two are indissolubly connected, it might be anticipated that the creation of a magnetic whirl round a wire by some external agency would create a simultaneous current in the wire. The truth of this was first experimentally verified by Faraday in 1831; his initial experiment proved that if magnetic lines of force are suddenly introduced into a hollow spiral of wire (the ends of which are joined together), a current is generated in the spiral so long

as the magnetic disturbance continues. Faraday gave the name **Induced Currents** to currents generated in this manner.

EXPT. 172.—Select a cylindrical coil consisting of many turns of fine cotton-covered copper wire [1] (10 layers of 40 turns each of No. 28 S.W.G. is convenient) wound on a hollow reel of sufficient internal diameter to allow a small bar-magnet to be readily inserted. Connect the ends of the coil to a mirror galvanometer (a d'Arsonval pattern will be found most suitable). Rapidly bring the north-seeking pole of a bar-magnet towards one end of the spiral, and observe the simultaneous deflection of the galvanometer-needle. Now suddenly withdraw the magnet and observe the deflection in the opposite direction.

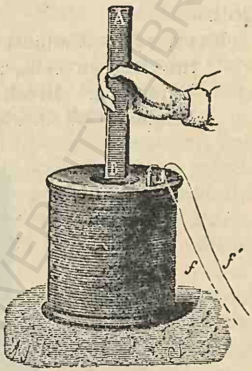


FIG. 195.—To illustrate Expt. 172.

From these results it is evident that when lines of force are either introduced into or withdrawn from the coil an induced current is obtained. It can also be observed that when the magnet is stationary, whatever its position relatively to the coil, no induced current is obtained—in fact, an induced current is only obtained when lines of force are being introduced into or withdrawn from the coil. Again, it can be observed in the same experiment that the *strength* of the induced current depends upon the *rate* at which the lines of force are being introduced or withdrawn; if the magnet is moved slowly, then only a weak induced current is obtained.

The same results may be obtained by using a spiral of wire, conveying a steady current, instead of a bar-magnet. The spiral should consist of fewer turns of thicker wire, and should be sufficiently small to be inserted completely within the coil. The magnetic lines of force due to the spiral may

[1] It is advantageous to have the turns of wire visible so that the direction in which the coil is wound may be observed.

be introduced into the coil either by conveying the spiral up to the coil from a distance, or by previously inserting it inside the coil and afterwards completing the circuit. Faraday termed the coil connected to the battery the **Primary Coil**, and the coil connected to the galvanometer the **Secondary Coil.**

EXPT. 173.—Connect up the Primary Coil to a battery of two Bunsen cells, and repeat the observations made in Expt. 172. Break the Primary Circuit and place the Primary Coil inside the Secondary Coil. Complete the

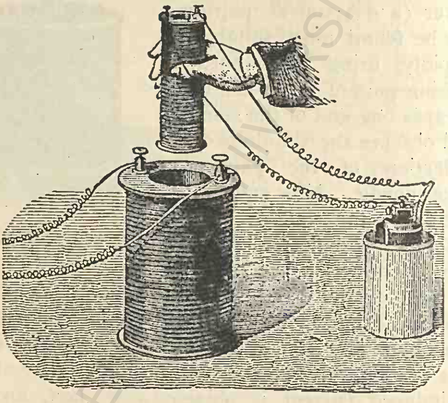


FIG. 196.

circuit and observe that the momentary induced current is in the same direction as when the Primary Coil (with its current) approached the Secondary Coil. Break the circuit and observe the momentary deflection in the opposite direction.

Since the strength of the induced current depends upon the rate at which lines of force are introduced or withdrawn, the effects observed in Expt. 173 will be considerably augmented if a core of soft iron is inserted inside the Primary Coil so as to form an electro-magnet.

EXPT. 174.—Repeat the observations in Expt. 173, but

using the Primary Coil with a soft iron core added. Notice how the induced currents obtained are much greater than when the soft iron core was not used.

So far, the magnetic lines causing the induced currents have been due either to a bar-magnet or to a coil of wire conveying a current. Can the same effects be obtained by means of the magnetic field surrounding a straight wire conveying a current? Lengths of wire sufficiently long to show the effects would be inconvenient to handle, but this difficulty can be overcome by winding the wires into flat spirals.

EXPT. 175.—Connect one spiral to the galvanometer, and the other spiral to a battery. Quickly bring the spirals together with their flat faces in contact, and observe the momentary induced current in the secondary spiral. Quickly separate the spirals and observe the induced current in the reverse direction.

Lenz's Law.—Energy, in some form or other, is required in order to generate an electric current. Whence is the energy obtained which gives rise to the induced currents observed in these experiments? It must be due to some external agency, and it originates from the mechanical work done in overcoming mutual electrical forces set up by the relative motion of the two circuits. If this is true, then the mutual electrical forces during approach of the two circuits should tend to hinder their approach, and they should tend to make the circuits approach during the process of separating them.

EXPT. 176.—Use the two spirals described in Expt. 175. Trace out the direction in which the current is traversing the primary spiral. Note the direction of the deflection obtained when the spirals are brought together. Determine by means of a voltaic cell in what direction the current must proceed between the galvanometer terminals in order to produce a deflection in the same direction; by this means we can determine in which direction the induced current traversed the secondary spiral. Verify that a momentary induced current in the *opposite* direction is obtained when the primary circuit is *approaching* (or when the two circuits are close together and the primary circuit suddenly

made); also that the induced current is in the *same* direction when the primary circuit is *receding* (or when the primary circuit is suddenly *broken*).

In each case the induced current is in such a direction as will tend to oppose the relative motion of the two circuits. This relationship holds good in all cases of current induction, and is expressed in the general statement of *Lenz's Law*. **The induced current is in such a direction that its reaction tends to stop the motion to which the induced current is due.** A further verification of this law may be derived from Expt. 173 if the polarity of the coil due to the induced currents is determined by tracing out the direction in which the wire is wound on the coil; *e.g.* the approach of a north-seeking pole will generate north-seeking polarity in the near end of the coil, while its withdrawal will generate south-seeking polarity in the same end.

Faraday's Law of Current Induction.—So far, we have only considered the *current* produced in these induction experiments. No current can be produced without the presence of an E.M.F. giving rise to it, and moreover the strength of the current depends upon the resistance of the circuit, whereas the E.M.F. is quite independent of the resistance. Hence it is more correct to consider the induced E.M.F. rather than the induced current. Induction effects would be obtained if the secondary circuit consists of only one turn of wire, although they would be so weak that it might be difficult to detect them. If the circuit consisted of two turns of wire in series, then the same E.M.F. would be induced in *each* turn, and the total E.M.F. between the extreme ends of the coil would be twice as great as that generated in a single turn; and if the coil consists of n turns, then the induced E.M.F. between the ends of the coil would be n times as great. If N lines of force are suddenly threaded through a coil of n turns, then the total number of lines of force threaded through the circuit will be $(N \times n)$, and the induced E.M.F. between the ends of the coil will be proportional to Nn. This result was experimentally verified by Faraday, and expressed in the following law:—**When the number of magnetic lines of force through a secondary circuit is changing an induced E.M.F. is set up, and the magnitude of the**

E.M.F. is proportional to the rate at which the number of lines of force changes.

The Rhumkorff Coil.—The Rhumkorff Coil is a practical application of Expt. 174, in which an induced E.M.F. is set up between the ends of a secondary coil by making and breaking the circuit of an electro-magnet which is placed inside the secondary circuit. Fig. 197 is a diagrammatic representation of the essential parts of the instrument. P is the primary coil with its core consisting of a bundle of soft-iron wires. The primary circuit is rapidly *made* and *broken* by the contrivance shown at M; a flexible spring is fixed vertically at A, and a piece of soft iron is attached to the upper end of the spring

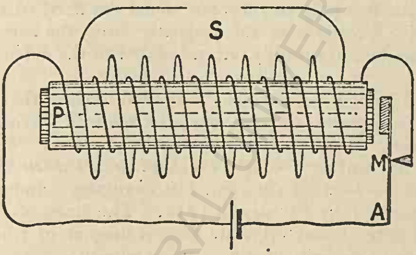


FIG. 197.—Diagram of a Rhumkorff Coil.

and near to the soft-iron core. When the primary circuit is made the current traverses the coil of wire and passes from the point (at M) into the spring, returning to the battery through A. The iron core becomes strongly magnetised and attracts the soft iron at the end of the spring, thus *breaking* the circuit at M. The iron core immediately ceases to be a magnet and the spring returns to its original position, thus *making* the circuit once more. This series of operations proceeds with great rapidity, and the spring vibrates rapidly to and fro, the circuit being made and broken in every complete vibration of the spring. The secondary coil, S, is wound round the primary circuit, and an induced E.M.F. is set up between its ends each time the primary is made or broken. In practice, P consists of several hundred turns of fairly thick silk-covered copper wire, and S consists of several thousand

turns of fine silk-covered copper wire. By having a sufficiently large number of turns of wire in S it is possible to obtain a sufficient potential difference between its ends to yield sparks 10 inches, or even 15 inches, long.

Chief Points of Chapter XXIII

Behaviour of a Linear Current in a Magnetic Field.—A single magnet-pole placed near to a wire conveying a current will tend to rotate round the wire in a circular path concentric with the wire (the direction of rotation can be deduced from Maxwell's Corkscrew Rule); if the magnet-pole is fixed and the wire conveying the current free to move, then the latter will rotate round the former in the same direction as the free pole would rotate round the fixed wire.

The relative directions of the magnetic force, the current, and the consequent motion, are readily remembered with the aid of the *Right-hand Rule.*

The Right-hand Rule may also be applied to show that *two parallel wires conveying currents in the same direction will attract each other, and if in opposite directions they will repel each other.*

Induced Currents *are set up in a closed circuit when the number of lines of force enclosed by the circuit is changing.* Induced currents were first observed by Faraday in 1831. The lines of force causing the induced current may originate from a magnet or from a spiral of wire conveying a current, or from a linear current.

The *Primary* and *Secondary Circuits* are terms introduced by Faraday in order to distinguish the *inducing* from the *induced* current.

Lenz's Law.—*The induced current is in such a direction that its reaction tends to stop the motion to which the induced current is due.*

Faraday's Law of Current Induction.—*When the number of magnetic lines of force through a secondary circuit is changing an induced E.M.F. is set up, and the magnitude of the E.M.F. is proportional to the rate at which the number of lines of force changes.*

Questions on Chapter XXIII

1. A wire conveying a current is placed in a magnetic field, the direction of the lines of force of which is known. Explain how the direction in which the wire will tend to move may be deduced from theory.

2. State the law of attraction and repulsion of straight wires conveying currents, and describe an experiment by which the law may be verified.

3. State the simple laws of electro-magnetic induction, and describe simple experiments illustrating them.

4. One pole of a strong bar-magnet is put through a copper ring and quickly taken out again. This is done repeatedly and quickly. Although the magnet and ring are not allowed to rub against each other, the ring becomes slightly heated. Why is this? (1881.)

5. How could you temporarily stop or weaken the current in a wire, without disconnecting it from the battery, by means of the motion of another wire through which a current is passing? (1883.)

6. A bar-magnet is allowed to drop vertically through a hank of insulated copper wire placed horizontally. What electrical effects, if any, are produced in the wire? (Coll. Precep. Prel. 1893.)

7. Describe experiments to prove that the current produced by moving a magnet tends to stop the motion, and that the motion produced by the magnetic action of a current tends to stop the current. (Lond. Matric. 1890.)

8. Supposing that a magnetic north pole is just below the middle of the sheet of paper on which you are writing, and that the south pole is distant, and supposing that a copper ring is laid flat on the paper and drawn across the middle of the sheet from left to right, draw figures at various points of the course, showing the directions of the induced currents, and give an explanation of your figures. (Lond. Matric. 1896.)

MISCELLANEOUS QUESTIONS FROM BOARD OF EDUCATION EXAMINATION PAPERS

Magnetism

1. A piece of iron when brought near to a small compass needle attracts one pole and repels the other; how would you ascertain whether it was permanently magnetised or only temporarily magnetised by the earth's magnetic field?
2. Sketch the lines of force of a bar magnet, with an equal bar of soft iron laid across its North pole so as to form a T.
3. A horsehoe magnet laid on the table near a compass needle produces a deflection of the latter. When the keeper of the magnet is placed near the poles, but not touching them, the deflection is diminished. How do you explain this?
4. The beam of a balance is made of iron. If the balance is placed so that the beam vibrates in a plane at right angles to the magnetic meridian, the beam is horizontal when equal weights are placed in the scale pans. What will happen when the balance is turned so that the iron beam swings in the magnetic meridian?
5. A bar magnet is placed with its axis in the magnetic meridian and its North pole turned towards the South. Describe and explain the behaviour of a small compass needle as it is carried along the prolongation of the axis of the magnet, both towards the North and towards the South.
6. Explain how the strength and direction of the earth's magnetic field at any given place is defined.

   If the horizontal force is .3 unit and the vertical force is .4 unit, what is the total force?

   Draw a diagram, by means of which the dip could be obtained.
7. A bar magnet one inch long, with its North pole pointing due East, is placed at a distance of four inches from a small compass needle due North of the centre of the magnet. How will the needle be deflected, and how will the deflection be altered

if a thick iron ring 2 inches in diameter is placed round the bar magnet?

8. How would you magnetise a bar magnet so as to have a South pole at either end and a North pole in the centre? How would the strength of the single North pole compare with that of either of the South poles, if the magnet was magnetised as uniformly as possible?

9. A wooden ball contains a bar magnet imbedded so that the axis of the magnet lies along a diameter, but the ends do not reach the surface. Explain carefully how you would mark on the surface of the ball the points where the axis of the magnet prolonged would cut the surface.

10. What is meant by the statement that the declination at a place is 18° West? At such a place how must a boat be steered by compass so that its course may be due East?

11. A horse-shoe magnet is brought due South of a small compass-needle, the line joining the poles of the magnet being East and West, with the North pole to the West. Describe the manner in which the compass is deflected.

Describe and explain what will happen if the keeper is placed on the magnet.

12. How would you hold a rod of soft iron so that the influence of the Earth's magnetic field upon it may be (1) as great as possible, (2) as small as possible?

13. What is meant by the axis of a magnet? Where is the axis of a horse-shoe magnet? In what direction would such a magnet place itself, if placed upon a wooden board floating freely in water?

14. What is meant by magnetic induction? Give a neat sketch showing how the lines of the Earth's magnetic field in a laboratory would be distorted if the ceiling were supported on iron pillars.

15. What are the most important points in the construction of a dip-needle? How should the axis of the needle be adjusted in taking observations of the dip?

16. A bar-magnet is carried in a horizontal circle round a compass needle with its North pole pointing always to the centre of the needle. How will the needle be affected when the magnet is North, East, South, and West, respectively, of the needle, assuming that the Earth's influence on the needle is always greater than that of the magnet?

Frictional Electricity

1. How would you show, by means of a condensing electroscope, that the poles of a voltaic battery are oppositely charged?

2. When a charged glass rod is brought near to an electroscope the leaves diverge, and fall together again when the rod is withdrawn. If a needle is placed on the cap of the electroscope, with the point projecting from it, and the experiment is repeated, the leaves diverge on approach of the glass rod, but remain divergent when the rod is taken away. Explain this.
3. A deep metal cylinder open at the top is placed on an insulating stand and charged with negative electricity: a metal sphere supported by an insulating thread is put in contact (*a*) with the outside, (*b*) with the inside of the can, and then brought close up to a positively charged gold-leaf electroscope. State and explain the effect produced on the electroscope in the two cases.
4. A Leyden jar held in the hand is charged from one pole of an electric machine, the other pole being earthed. What difference will it make if the person holding the jar stands (1) on an insulating stool, (2) on the ground?
5. Explain what is meant by electrostatic induction.

   Two small light pith-balls are in contact, and are supported by separate threads. A charged glass rod is brought in the neighbourhood of the balls. What will happen (*a*) when the threads are wet and conducting, (*b*) when they are dry and insulating?
6. Describe and explain the action of the electrophorus.

   The electrophorus is used to charge a Leyden jar. Carefully explain whence the energy corresponding to the charge of the jar is derived.
7. Two pith-balls are charged positively, and suspended by silk fibres, one inside, the other outside an insulated metal cylinder. Describe and explain the behaviour of the pith-balls when the cylinder is charged (*a*) positively and (*b*) negatively.
8. A long cylindrical conductor is charged with electricity. Give a sketch showing how the electricity is distributed over its surface. A gold-leaf electroscope is connected by an insulated wire first to the middle and then to either end of the cylinder. Describe and explain the indications of the electroscope in each case.
9. Two large insulated metal plates, *A* and *B*, are placed parallel and close together, but not touching. *A* is connected to an electroscope. A small charge is given to *A*, causing the leaves to diverge. The plate *B* is touched with the hand, then removed to a considerable distance, and, lastly, allowed to touch *A*. Describe and explain the behaviour of the electroscope in the three cases.
10. How may the heat developed by an electric discharge be demonstrated? Describe a simple form of experiment, and explain how it should be performed.

11. Describe and explain the action of a gold-leaf electroscope. Having charged the instrument positively, how would you test the sign of the charge on the inner coating of a Leyden jar without discharging or moving either the jar or the electroscope?
12. What is meant by the statement that a given body is at a higher potential than the earth? Illustrate your answer by means of analogous phenomena in heat and hydrostatics.
13. A hollow metal can is placed on an insulated stand and electrified. Describe the distribution of the electrification on the can, and explain how you would examine the distribution experimentally.
14. A metal plate *A*, thickly varnished on the top, is insulated and connected to a gold-leaf electroscope, the whole being charged with positive electricity until the leaves diverge widely. When another insulated plate *B* (for instance, the cover of an electrophorus) is placed on the top of *A*, the divergence of the leaves is very little altered, but if *B* is touched the leaves fall nearly vertical. How do you explain these effects?
15. Describe and explain the action of a plate-glass frictional machine. How would you use it to charge a Leyden jar?
16. A point-charge is placed near a conducting sphere. Describe the distribution of electricity on the sphere (*a*) when the sphere is insulated and uncharged; (*b*) when connected to the earth.
17. Two insulated spheres *A* and *B* are placed near together, and *A* is charged positively. How is the potential of *B* affected by the presence of *A*, and how will it be modified if *B* is touched with the finger, and *A* then removed?
18. A hollow metal vessel is insulated and charged with electricity. How is the electricity distributed, and how is the distribution modified (if at all), when a metal rod held in the hand is introduced into the vessel without touching it?
19. Describe the construction of a Leyden jar and the method of charging it. What do you understand by the capacity of such a jar?
20. How would you prove that positive and negative electricities are developed in equal quantities (*a*) by friction, (*b*) by induction?

Voltaic Electricity

1. In what respects does the current produced by a voltaic cell differ from the discharge of an electric machine? What do you understand by the strength of a current, and by what effects may the strength be measured?
2. Describe the construction of, and the chemical action which takes place in a Leclanché cell. Is this a constant cell? If not, why not?

3. Does a straight copper wire through which an electric current flows attract or repel a magnetic pole? How do you explain what happens when such a wire is plunged into iron filings?
4. An electric current is passed through a platinum wire and a copper wire of the same size, arranged in series. If the strength of the current is sufficiently increased, the platinum becomes red-hot while the copper remains dark. Explain this.
5. Show that a galvanometer with a single needle may be made more sensitive by placing a magnet in a suitable position in its neighbourhood. Give a sketch showing how you would mount the magnet so that by moving the magnet the sensitiveness may easily be altered; indicate the position of the poles of the magnet when the sensitiveness of the instrument is as great as possible.
6. Describe the Daniell and Leclanché cells, and explain carefully the functions of the different parts.

   Why is the Leclanché cell used in preference to the Daniell cell for working electric bells? Which type would be the better for lighting a small incandescent lamp?
7. Two platinum plates, connected to the poles of a battery of several Bunsen cells, are dipped into a solution of copper sulphate. Describe the changes that take place due to the passage of the current. What would be the effect of using copper plates in place of platinum?
8. Describe some sensitive form of galvanometer, and explain how you would set it up to measure a very small current.

   If you found that the deflection produced was off the scale, how would you reduce the sensitiveness of the galvanometer?
9. A single cell is connected to a galvanometer by long fine wires, giving a deflection of 10°. If a second similar cell is connected in parallel with the first, the deflection becomes 11°, but if connected in series, the deflection is increased to 19°. Explain this.
10. Draw a plan showing how the current must circulate in the coils of a horse-shoe electro-magnet, to make the poles (*a*) both North, (*b*) one North and the other South.
11. Describe the Daniell cell, and explain the functions of each part of the cell and the action that takes place when the poles are connected by a conducting wire.

    What advantages does this form of cell possess over a simple voltaic cell consisting of plates of copper and zinc immersed in dilute acid?
12. State Ohm's Law, and explain the terms used.

    An incandescent electric lamp takes a current of 0.5 ampere when connected to a circuit of 100 volts. What is the resistance of the lamp?

13. Explain how you would wind a U-shaped piece of soft iron with wire, and how you would connect the wire to a battery so as to form an electro-magnet with two North poles at the tips of the U. Carefully describe the magnetic state of the iron when a current is passing through the winding.
14. Describe some simple form of galvanometer, and explain the method of using it.
15. Assuming that the rate of production of heat by a current in a wire varies as the product of the resistance and the square of the current, compare the amount of the heat developed by a current of 2 amperes in 3 minutes in a wire 3 feet long, with that produced by a current of 3 amperes in 2 minutes in 2 feet of the same wire.
16. What is meant by the Electromotive Force of a voltaic cell? If you were given two cells, how would you test which had the greater electromotive force?
17. Describe how a compass needle will be affected by a current flowing in a long straight wire (*a*) from South to North, (*b*) from East to West, when the wire is placed above, below, or at the side of the compass.
18. A plate of zinc and a plate of copper are placed in dilute sulphuric acid. What action takes place, if any? How is the action modified, (1) if the zinc is amalgamated, (2) if it is connected to the copper plate?
19. The poles of a Daniell cell are connected by one yard of fine wire, and the current observed. The length of the same wire is increased to 3 yards, and the current is thereby reduced to one-half. Compare the amounts of heat developed in the wire in the two cases.
20. Insulated wire is coiled on a glass tube placed horizontal and at right angles to a compass needle, the centre of which lies on a prolongation of the axis of the tube. How will the needle be affected when the current is passed through the coil? Will the introduction of an iron rod or a copper rod into the tube make any difference?

MISCELLANEOUS QUESTIONS FROM LONDON UNIVERSITY MATRICULATION EXAMINATION PAPERS.

Magnetism

1. Explain the meaning of the terms *magnetic declination* and *dip*. In determining magnetic dip it is customary, after having made one set of observations, to reverse the magnetisation of the needle and then to make another. Show that this enables us

to eliminate error due to any want of coincidence between the centre of gravity of the needle and its axis of suspension.

2. What is meant by a *uniform magnetic field?*

A steel rod hangs vertically from the pan of a balance and its weight is observed. It is then magnetised strongly and weighed again with the North-seeking pole pointing vertically downwards. Will any change be observed?

What will be the effect upon the apparent weight of the rod, before and after magnetisation, of holding under it a thin disc of soft iron (1) with its plane faces vertical, (2) with its plane faces horizontal?

Give reasons for each part of your answer.

3. Describe fully how a compass needle placed in the middle of a steel ship, built with its bow pointing North, would be affected during the motion of the ship as it swung round completely in a clockwise direction, if the field at the centre of the ship due to its magnetisation could be assumed to remain constant in direction with respect to the ship, and to be equal in magnitude to the Earth's field.

4. What is meant by a *line of magnetic force?*

Draw diagrams showing the lines of force due to two equal bar magnets, each 1 foot long, placed in line 1 foot apart with (1) opposite and (2) like poles facing each other. Show how the lines of force are affected in each case by placing a bar of iron, 10 inches long, in line with the magnets and midway between them.

Describe the magnetic state of the iron in each case.

5. A bar magnet 30 cms. long is placed in the magnetic meridian, and it is found that a small compass needle, placed on the axis of the magnet produced at a distance of 30 cms. from one pole, will point in any direction. How would you explain this? State which pole of the magnet points Northward.

If the strength of the Earth's horizontal field is 0.18 C.G.S. unit, what is the pole strength of the magnet?

6. The beam of a chemical balance is made of iron. When it lies in the magnetic meridian, a substance placed in one pan appears to weigh 50 grammes. On turning the balance round so that the end that originally faced North now faces South, the weight appears to be 50.2 grammes. Explain these facts.

7. A long steel wire is magnetised uniformly. Two pieces, each 6 inches long, and two others, each 4 inches long, are cut from it, and these four pieces are arranged so as to form a rectangle with two North poles together at each of two opposite angles.

Draw the lines of force of the rectangle. In what position would it set if it were placed horizontally upon a cork floating in water?

8. Draw a section of the Earth through its centre, and represent the general forms of its lines of magnetic force. How is the direction of the lines of force at a given locality found by experiment?
9. AB is a thin magnet 20 cms. long, the strength of each of its poles being 12 units. Upon AB as base an equilateral triangle ABC is constructed. Find the magnitude and direction of the force that a unit pole would experience if it were placed at C. Also the force upon the magnet caused by the unit pole at C.
10. A bar magnet pointing towards the centre of a compass needle and at a certain distance from it causes the needle to take up a position at right angles to the magnet. Give a diagram showing the directions of all the magnetic forces acting on each pole of the needle, and show that the resultant forces on the two poles of the needle due to the magnet are equal in magnitude.
11. A steel rod is magnetised in the direction of its length. What effect would be produced upon the external field due to the rod if it were placed within a soft iron tube of equal length and of internal diameter slightly greater than the diameter of the rod? Describe how you would find by experiment the proportion in which the field due to the rod, at a given point on its axis produced, was altered owing to the presence of the tube.

Electrostatics

1. Two gold leaves attached to the end of a glass rod are positively charged and diverge from one another. What effect, if any, is produced on the divergence (1) when a spherical metal pot, connected to earth, is placed so that the leaves are at its centre, (2) when, after insulating the pot, a gradually increasing positive charge is given to it? Give reasons.
2. Two circular metal discs, of 50 cms. radius, are placed parallel to one another 1 cm. apart, and are equally and oppositely charged. Draw a diagram showing fully the directions of the lines of force between them. If the difference of potential between the discs is 10 C.G.S. units, find the force which would be experienced by a small particle containing 0.005 unit of electricity when placed midway between them.
3. Explain fully the meaning of the formula $\frac{1}{2}cv^2$ which represents the energy of a condenser.

   A charged condenser is made to share its charge with another uncharged condenser of the same size by joining corresponding terminals by thin insulated wires. What effect is produced upon (1) the charges on the plates, (2) the potential difference

between the plates, and (3) the electric energy of the first condenser? Give reasons.

4. Describe experiments to show that there are two kinds of electrification. Upon bringing an electrified glass rod towards a previously unelectrified ball suspended by a silk thread the ball is attracted. Explain this, and describe experimental evidence in support of your explanation. Would a previously unelectrified glass ball be attracted by an electrified body? Give reasons for your answer.

5. A small metal sphere is hung by a silk thread from one pan of a balance and is counterpoised by weights placed in the other. A second insulated and electrified metal sphere of equal radius is made to touch it for a moment, and is then fixed at a distance of 10 cms. below the first. It is found as the result that the counterpoise has to be reduced by 0.001 gramme to restore equilibrium. Find the charge on each sphere.

   What precautions would it be necessary to take to perform this experiment successfully?

6. Equal and opposite charges are imparted to two insulated brass spheres, each of one-inch radius with their centres 6 inches apart. Make a careful drawing of the lines of force of the system.

   Represent upon other diagrams the effect of placing (1) a metal sphere of one-inch radius; (2) a glass sphere of one-inch radius, midway between them.

7. Water escapes from a small earth-connected metal jet directed vertically downwards, breaking into separate drops immediately upon leaving it. Near the jet, with its centre in a horizontal line with it, is a positively electrified sphere. The drops fall into an insulated can, and this is found to become more and more strongly electrified. Explain this.

   If the insulation of the sphere and can were perfect the drops would after a time cease to fall into the can. Explain this and show where they would fall.

8. Describe the action of a gold-leaf electroscope provided with a condensing plate, and explain how you would use it to detect the electrification of a large feebly electrified sphere.

9. An insulated electrified metal plate having a charge of 1000 units is placed between two parallel earth-connected metal plates each equal to it. One of these plates is $\frac{1}{10}$ inch, and the other 1 inch from the first. Determine the charges induced upon the plates. How would the potential of the insulated plate be affected if the first of the earth-connected plates were removed?

10. A small positively charged ball is lowered through an opening in a hollow uncharged insulated sphere. Draw careful diagrams

of the lines of force when the ball is (1) just outside, (2) just inside, (3) at the centre, (4) touching the bottom of the sphere.

Describe the distribution of electricity in each case.

11. Two condensers have square discs as plates. In one the discs are of 10 cms. side, and are 2 mms. apart; in the other the discs are of 5 cms. side, and are 1 mm. apart. Which condenser has the greater capacity? If they were charged, how could you find which had (1) the greater potential difference, (2) the greater charge? Give reasons in each case.

12. What do you understand by the strength of a uniform electric field?

Calculate the strength of a uniform field which is such that an erg of work is done upon a body containing half a unit of electricity when moved through a metre in the direction of the field.

13. Describe an experiment showing that electric charges produced by friction are opposite in kind and equal in amount.

Describe some simple machine by which a continuous supply of such charges can be produced.

14. Describe the construction of a gold-leaf electroscope, paying special attention to those features of the instrument upon which its efficiency depends.

Draw the lines of force inside a gold-leaf electroscope when the leaves are positively charged and hang between two earth-connected plates placed inside the electroscope. What effect would be produced upon (1) the lines of force, (2) the divergence of the leaves, by removal of the plates in question?

15. What is meant by *the strength of an electric field?*

The points A, B, C, and D are at the corners of a square in a uniform electric field of which the direction is parallel to AB and to DC. If AB is 10 cms. in length, and 5 units of work are done in carrying 3 units of electricity from B to A, what is the strength of the field? What is the difference of potential between B and D?

16. Two metal spheres A and B, of equal radii, are mounted on insulating stands. They are placed in front of a large vertical metal sheet C, B being midway between A and C. The sphere A is positively charged. Draw diagrams to represent approximately the electric field, (1) when B is kept insulated, (2) after it has been momentarily connected to earth.

What can you infer from the diagrams as to positions of no force in the field in the two cases?

17. Explain fully what is meant by the capacity of a condenser.

Describe the experiments you would perform to determine how the capacity of the condenser depends upon (1) the size of the plates, (2) their distance apart, (3) the nature of the insulator between them.

18. An insulated metal sphere A is positively charged. Another insulated sphere B of equal radius, but uncharged, is momentarily brought into contact with it and then removed. What will be the ratio of (1) the charge, (2) the potential, (3) the electric energy of A after contact to the value of each of those quantities before contact?

Show that the combined electric energy of A and B is less than the original electric energy of A. In what manner has the loss been incurred?

Voltaic Electricity

1. A current flows down a vertical wire, and is of such strength that at a distance of one foot from it its magnetic field is equal to the horizontal field of the earth. Indicate in a diagram the directions in which a freely suspended compass needle would set if carried round the wire at a distance of one foot from it, when the needle is N., N.E., E., S.E., S., S.W., W., and N.W. of the wire.
2. The plates of a cell, the resistance of which is inappreciable, are connected by a platinum wire. How would the rate of development of heat in the wire, and the rate of consumption of zinc in the cell, be affected if the wire were drawn out uniformly to double its length?
3. Four wires, AB, BC, CD, and DA, are arranged so as to form a rectangle, and their resistances are 1, 2, 3, and 4 ohms respectively. The opposite corners A and C are then connected to a voltaic cell of E.M.F. 2 volts. If, as the result, the difference of potential between A and C is 1.4 volts, determine the difference of potential between B and D.

   Show that if B and D were connected by a thick copper wire of no appreciable resistance, the current in AB would be four times that in AD.
4. A coil of wire is wound upon the north pole of a magnet, and the pole is then presented to a piece of iron which it draws towards it. Determine the direction of the current induced in the coil.

   In what form has energy disappeared to appear as heat developed by the current.
5. Describe some form of secondary battery. State (1) how you would charge it; (2) which would be the positive pole.

   What are the advantages and disadvantages of such a battery as compared with a Leclanché cell?
6. A battery, of which the E.M.F. is 1 volt and the internal resistance 1 ohm, is connected to a galvanometer of which the resist-

ance is 2 ohms. What is the current in the circuit? How is the current through the galvanometer affected by joining its terminals by a wire of 2 ohms resistance?

7. A coil of insulated wire, of which the ends are joined, is suspended by a long fine thread from a point in its circumference. A bar magnet is moved suddenly towards the coil (which is protected from air currents) along a line perpendicular to the plane of the coil and passing through its centre. What effect is produced upon the position of the coil?

Does the effect depend upon (1) the initial position of the coil with respect to the meridian? (2) the number of turns in the coil? Give reasons.

8. How would you proceed and what data would you require in order to measure a given current in amperes by means of (1) a tangent galvanometer; (2) electrolysis of copper sulphate?

What do you consider to be the relative advantages and disadvantages of the two methods?

9. A storage cell with a single pair of plates connected by a wire of 0.8 ohms resistance gives the same current as a similar cell, with plates twice as broad, twice as deep, and twice as far apart, which are connected by a resistance of 0.9 ohms. Find the resistance of each cell.

Why are the plates of a storage cell usually of large surface?

10. Two coils of insulated wire lie, one inside the other, on a table. The outer is in series with a galvanometer; the inner can be connected in series with a battery of inappreciable resistance. Describe and explain the indications of the galvanometer when a current is made, kept on for some time, and then interrupted in the inner coil.

Would the indications be different on repeating after (1) reducing the number of turns of wire in the inner coil; (2) placing the inner coil upright? Give reasons.

11. The terminals of a voltaic battery of resistance 1 ohm are connected by two wires *in parallel*, their resistances being 6 and 8 ohms respectively. The difference of potential between the terminals is 2 volts. Find the currents, and compare the rates at which energy is expended in the wires. Find also the electromotive force of the battery.

12. Describe the nature of the influence that a current flowing in a long straight wire exerts (i) upon a magnetic pole, (ii) upon a small magnet capable of turning in any direction, in its neighbourhood.

Explain the fact that iron filings cling round a wire traversed by a strong current.

13. Describe the construction and explain the action of the induction coil, ignoring the condenser.

14. What is a *storage cell?* State the general principle of its action. A storage cell is frequently said to store electricity. Criticise this statement. What does it really store?
15. Represent in a diagram the arrangement of the parts of an ordinary *electric bell*, and explain its action.
16. Being given 4 voltaic cells, each of E.M.F. 2 volts and resistance 0.2 ohm, find the currents they would produce in external resistances of 0.1 ohm and 1 ohm respectively when the cells are connected up (1) in parallel and (2) in series. Find also the differences of potential between the ends of each external resistance for each arrangement of the cells.
17. The E.M.F. of a storage cell is almost exactly double the E.M.F. of a Daniell. How would you test this statement without the aid of a galvanometer? How do you explain the difference of E.M.F.? Describe carefully the chemical changes that would occur in a Daniell if it were connected, in opposition, to a storage cell.
18. Upon what factors does the internal resistance of a battery depend?

    A current is sent through a wire of 0.5 ohm resistance by attaching its ends to the terminals of a Daniell cell of internal resistance 0.5 ohm. What is the resistance of a second Daniell if when it is connected in series with the first the current is unaltered?

    In what proportion would the current through the wire alter if the cells were joined to it in parallel? Explain how you obtain your results.
19. A glass tube corked at the lower end is fixed in a vertical position and a number of turns of wire, the ends of which are connected to the terminals of a galvanometer, are wound around it. Iron filings are now poured into the tube. The tube is next tapped smartly. Finally the cork is withdrawn and the filings escape. Describe and explain the behaviour of the galvanometer during each of the three above operations.

BOARD OF EDUCATION

Magnetism and Electricity

STAGE I

1907 (*Day Paper*)

You are not permitted to answer more than *eight* questions.

You may select only *two* in Magnetism, *three* in Frictional Electricity, and *three* in Voltaic Electricity.

Magnetism

1. How would you test whether a steel bar is magnetised or not?

   If not magnetised, how would you proceed to magnetise it?

2. A short iron bar is suspended from the north pole of a magnet. If the south pole of a similar magnet is presented to the lower end of the bar, it remains suspended; but if the north pole is presented, the bar usually drops off the first magnet. Explain this.

3. Describe how the magnetic dip varies from place to place on the earth's surface.

   Draw a diagram showing how the assumption of a magnet at the centre of the earth can roughly account for the facts.

A bar of soft iron is placed on a horizontal table with its axis parallel to the Earth's field. Give a sketch showing the general disposition of the lines of force in the neighbourhood of the iron bar.

Frictional Electricity

5. Describe two experiments showing that the charge on a hollow insulated conductor is confined to the outside surface.

6. Describe the essential points in the construction of a gold-leaf electroscope, and explain how the sign of its charge may be tested without discharging it.

7. A cake of shellac is excited with negative electricity. Explain how to obtain equal charges of positive and negative electricity from it without discharging it.

8. A small metal sphere is suspended by a long dry cotton thread. The sphere having been charged positively is held inside an uncharged metal pot, which rests on the cap of a gold-leaf electroscope, but the sphere is not allowed to touch the pot. After the sphere has been in place for a few seconds the electroscope is momentarily earthed, and then the sphere remaining in place, the leaves of the electroscope are watched. Describe and explain the movements of the gold leaves, starting from the moment when the charged sphere was first introduced.

9. What precautions would you take if you wished to ensure that when glass and silk are rubbed together each is electrified?

   How would you prove that, if electrified, their charges are equal and opposite?

Voltaic Electricity

10. A plate of copper and a plate of amalgamated zinc are placed in a cell of dilute sulphuric acid. Describe what takes place in the cell when the plates are allowed to touch each other.

11. A magnet is placed at the centre of a circular coil of wire through which a current is passed. What is the direction of the force acting on the north pole of the magnet, and how does the force depend on the direction of the current?
12. Two wires are connected in series with a voltaic cell, the resistance of the cell being very small compared to that of either wire, and it is found that the heat developed in one wire is twice that developed in the other. Compare the quantities of heat developed per second when the wires are in turn connected to the same cell.
13. Describe carefully what takes place when an electric current is passed through a solution of copper sulphate (1) with platinum electrodes, and (2) with copper electrodes.
14. Describe how to construct an electromagnet, indicating carefully which end will develop a north pole.

1907 (*Evening Paper*)

Magnetism

1. An unmagnetised bar of soft iron is laid on a horizontal table in a north and south direction; what is its magnetic state?

   How will its magnetic state be altered if the end of the bar which is towards the north is raised until the bar is vertical?
2. Explain carefully how you would magnetise a strip of steel, so that one end, marked A, may become a north pole. Give reasons for the various operations you would perform.
3. A steel rod when tested is found to have a north pole at each end. What would you expect the magnetic condition of the intermediate portion to be, and how would you test your prediction?
4. Define *dip, horizontal component of the earth's field.*

   If at a place A the vertical component is found to be halt the horizontal component, what is the value of the dip? At what part of the earth's surface would you expect A to be situated?

Frictional Electricity

5. Describe a gold-leaf electroscope.

   When a charged rod of sealing wax is held at a certain distance from an electroscope the leaves diverge; they fall when the cap of the electroscope is momentarily touched, and diverge again when the sealing wax is removed. Explain these results.
6. A point is said to discharge electricity; describe three experiments in which such discharge takes place.

7. How did Faraday show that the energy of a charged Leyden jar resides in the dielectric?
8. A hollow insulated metal sphere contains two small insulated spheres, one charged with 2 units, and the other with 3 units of positive electricity. What will the consequent charge be on (*a*) the outside and (*b*) the inside of the hollow sphere?
9. Describe the electrophorus and explain carefully how it acts.

Voltaic Electricity

10. What is meant by local action in a voltaic cell?

    Why is such action objectionable, and how may it be prevented?
11. A small compass needle is suspended at the centre of a vertical copper ring through which a current is passed. How is the needle affected by the current (1) when the ring is in the magnetic meridian, and (2) when it is at right angles to the magnetic meridian?

    What are the forces acting on the needle in each case?
12. Describe an astatic system for a galvanometer, and explain carefully the reason for using such a system, and how the coils of the galvanometer are arranged with reference to the magnets composing the system.
13. How does the heat produced by a current depend upon the strength of the current?

    Describe how you would experimentally prove the relation.
14. A cell having an E.M.F. of 2 volts and a resistance of 0.5 ohm is connected up with three lengths of wire having resistances of 1, 2, and 3 ohms respectively, the wires being in series. Find the difference in potential between the ends of the middle wire.

UNIVERSITY OF LONDON MATRICULATION EXAMINATION

Electricity and Magnetism

June 1907

1. A bar magnet is suspended horizontally from its centre, and has a bar of hard steel, of the same dimensions, attached to it lengthwise, the two bars being kept separated by a thin strip of wood. The system is set oscillating in the magnetic field of the earth. Describe and explain the change you would observe in the rate of oscillation if the bar of hard steel were replaced by a bar of soft iron of the same dimensions.

2. Draw careful diagrams to exhibit the distribution of the horizontal lines of force in the region surrounding a bar magnet laid along the magnetic meridian with its North-seeking pole pointing (*a*) to the North, and (*b*) to the South. What can you infer from your diagrams as to regions of no force in the two cases?
3. Explain how an electrophorus can be used to obtain considerable quantities of electricities of opposite signs with only a small initial charge.

   What is the essential difference between the principle of the action of an electrophorus and that of a frictional machine? Explain fully.
4. A long hat-pin with a spherical metal head is insulated and placed upright above an insulated metal disc, one end being close to the surface of the disc. A positively charged insulated ball is now held near the upper end of the pin for a short time. The pin is then removed without being allowed to touch either the disc or the ball. Describe and explain the changes in the electric states of the disc, pin, and ball during the experiment (1) when the head of the pin, (2) when the point of the pin, is uppermost.
5. Two equally and oppositely charged insulated plates, each connected to an electroscope, are at a considerable distance apart. The plates are brought nearer together gradually until they are almost within sparking distance. Describe and explain (1) the behaviour of the leaves of the electroscopes, (2) the changes in the potentials of the plates, and (3) the change of electric energy of the system during the movement of the plates.
6. Describe and explain the action of some form of sensitive galvanometer with which you are acquainted, pointing out in detail the factors that contribute to the sensitiveness.
7. A coil of bare German silver wire of known length is attached to the terminals of a storage cell, and is observed to become warm. Why is this, and what are the factors that determine the rate of generation of heat within the wire?

   What length of German silver wire, of half the cross-sectional area of the above one, must be joined in series with it so that the rate of generation of heat within the first wire may be reduced by three-fourths?
8. Two plates of platinum, connected to a storage battery, are set vertically at some distance apart in a beaker of pure water, and a galvanometer is included in the circuit. A little sulphuric acid is then added to the water. Explain carefully the change produced by the acid, describing the actions that take place in the liquid and at the two plates.

   Explain the sense in which you understand the statement

that "water conducts when it is acidulated, and is decomposed by the current that passes."

September 1907 (*Morning Paper*)

(Two papers are sometimes set in order to compress the examination into as short a period as possible, but no candidate is allowed to take more than one paper.)

1. A compass needle, placed with its centre 20 cms. East of that of a bar magnet which lies at right angles to the meridian, is deflected through an angle of 45° out of the meridian. State the inference you would draw from this, and explain why the angle of deflection is independent of the strengths of the poles of the needle.

   The bar magnet is now turned so that it lies in the meridian with its South-seeking pole pointing North, and the compass is placed with its centre 20 cms. due North of that of the bar magnet. Describe and explain the behaviour of the needle, and draw the lines of force in the region surrounding it.

2. Describe carefully what is meant by the statement that the time of oscillation of a compass needle is inversely proportional to the square root of the strength of the field in which it swings.

   A compass needle makes five oscillations per minute under the influence of the Earth's field. It makes seven oscillations per minute when a long bar magnet is held vertically with its North pole in the same horizontal plane as the needle and at a given distance due South of it. How many oscillations per minute will the compass make when the poles of the magnet are reversed?

3. Two small metal spheres *A* and *B*, the radius of *A* being double that of *B*, held by silk threads and connected by a long thin wire, are charged by an electrophorus. They are then disconnected, and *A* is brought momentarily into contact with an uncharged metal sphere of the same radius. If the spheres *A* and *B* are now successively lowered into a deep metal can connected by a wire to the cap of an electroscope, but without touching the can, describe and account for the indications of the electroscope in the two cases.

   Finally, if the spheres are brought momentarily into contact outside the can and again successively lowered into the can, how will the indications of the electroscope differ?

4. Explain what is meant by the potential of an electrified body.

   State, giving reasons, whether it is possible (*a*) for an electrified body to be at zero potential, and (*b*) for an unelectrified body to be at a high potential, and describe some simple experiments to illustrate your answer.

5. A sphere held by a silk thread is "fully" charged by an electrophorus. It is then discharged, lowered into a deep metal can lying on the table (but without touching the can), and again "fully" charged. State what is meant by the term "fully" charged in these cases, and carefully explain in which of the two cases, and why, the charge would be greater.

   What difference would you observe in the second case if the can contained paraffin oil?

6. Describe a storage cell or accumulator, and explain the advantage of using large plates.

   Explain the experiments you would perform in order to distinguish between three cells—one a storage cell, another a Daniell, and the third a Leclanché—of which the terminals only were accessible in each case.

7. Describe the essential differences between a tangent galvanometer constructed for the measurement of a large current in amperes and a galvanometer designed for the detection of very minute currents.

   Would it be possible to so modify the method of working with a galvanometer of the second type that large currents could be compared by means of it? Explain fully.

8. A copper disc, freely suspended by a point in the rim, hangs between the poles of a powerful horse-shoe magnet. The line passing perpendicularly through the centre of the disc is at right angles to the line joining the poles of the magnet, and a bar magnet is brought suddenly near the disc along this line. Explain in detail why the approach of this magnet causes the disc to turn, and describe experiments to prove that your explanation is correct.

September 1907 (*Afternoon Paper*)

1. Explain why a magnet does not tend to move bodily along the lines of force in a uniform magnetic field.

   A steel rod hangs vertically from the pan of a balance and its weight is determined. It is then magnetised strongly and again weighed. Will any change be observed? Will any change be produced upon the apparent weight of the rod, before and after magnetisation, if a rod of soft iron is held vertically underneath it during the weighing? Give reasons in detail.

2. A bar magnet is placed in the meridian with its North-seeking pole pointing North. Show that there are in general two points, on the line perpendicular to the meridian passing through the centre of the magnet, at which the field due to the magnet is equal and opposite to the horizontal field of the Earth.

   The length of the magnet being 10 cms. and its moment 200;

calculate the strength of the Earth's field if the points of no horizontal force are 10 cms. distant from each pole of the magnet.

3. A vertical insulated metal plate A is positively charged. Some distance away another vertical metal plate B is connected to Earth. Between the plates two equal metal spheres C and D are fixed on insulating stands at equal distances from each other and from the plates. Draw three careful diagrams to illustrate the distribution of the lines of force between the plates (*a*) before C and D are connected together, (*b*) after they are momentarily connected together, and (*c*) after they are momentarily connected to Earth. What can you deduce from the diagrams as to regions of no electric force between the plates in the three cases?

4. A metal ball held by a silk thread is lowered into a deep positively charged metal can standing upon an insulating stand; it is allowed to touch the bottom of the can, and is then withdrawn. It is again lowered into the can, momentarily connected to Earth, but without being allowed to touch the can, and a second time withdrawn. State, giving reasons, what the potential of the ball is, and what is its electrical charge, if any, when inside the can, and when withdrawn in the two cases. If, in the latter case, the ball had been allowed to touch the can before being withdrawn, what change would have been produced in the potential of the can?

5. Describe the ordinary electrophorus, and the method of charging a conductor by means of it, explaining how the energy of the charge on the conductor is obtained.

   Is there a limit to the amount of the charge that can be given by the electrophorus to the conductor? Give reasons for your answer.

6. Describe and explain carefully the experiments you would perform in order to find whether the electromotive force of a Daniell cell depends upon the size of the plates. Give an explanation of the result you would expect to find.

   How do you account for the fact that, in any battery in which zinc forms one of the plates, the current within the cell may be expected to flow from the zinc to the other metal?

7. The coil of a given tangent galvanometer can be rotated about a vertical axis while the scale upon which the deflection of the needle is read remains fixed. Describe and explain in detail how the deflection of the needle will alter (the current through the coil remaining constant) when the coil is turned continuously through 360° from its original position in the meridian.

8. State and explain Faraday's law of electrolysis. Describe in detail how you would find experimentally the ratio of the electrochemical equivalents of hydrogen and copper.

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